**US Army Corps
of Engineers**
Waterways Experiment
Station

AD-A269 844

Performance Tests with the WES 4-Ft-Diameter Vertical Gas Gun

*by Howard G. White
Structures Laboratory*

DTIC
ELECTE
SEP. 23 1993
S B D

93-22338

93 9 2 020

Prepared for Defense Nuclear Agency

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

Performance Tests with the WES 4-ft-Diameter Vertical Gas Gun

by Howard G. White

Structures Laboratory

U.S. Army Corps of Engineers
Waterways Experiment Station
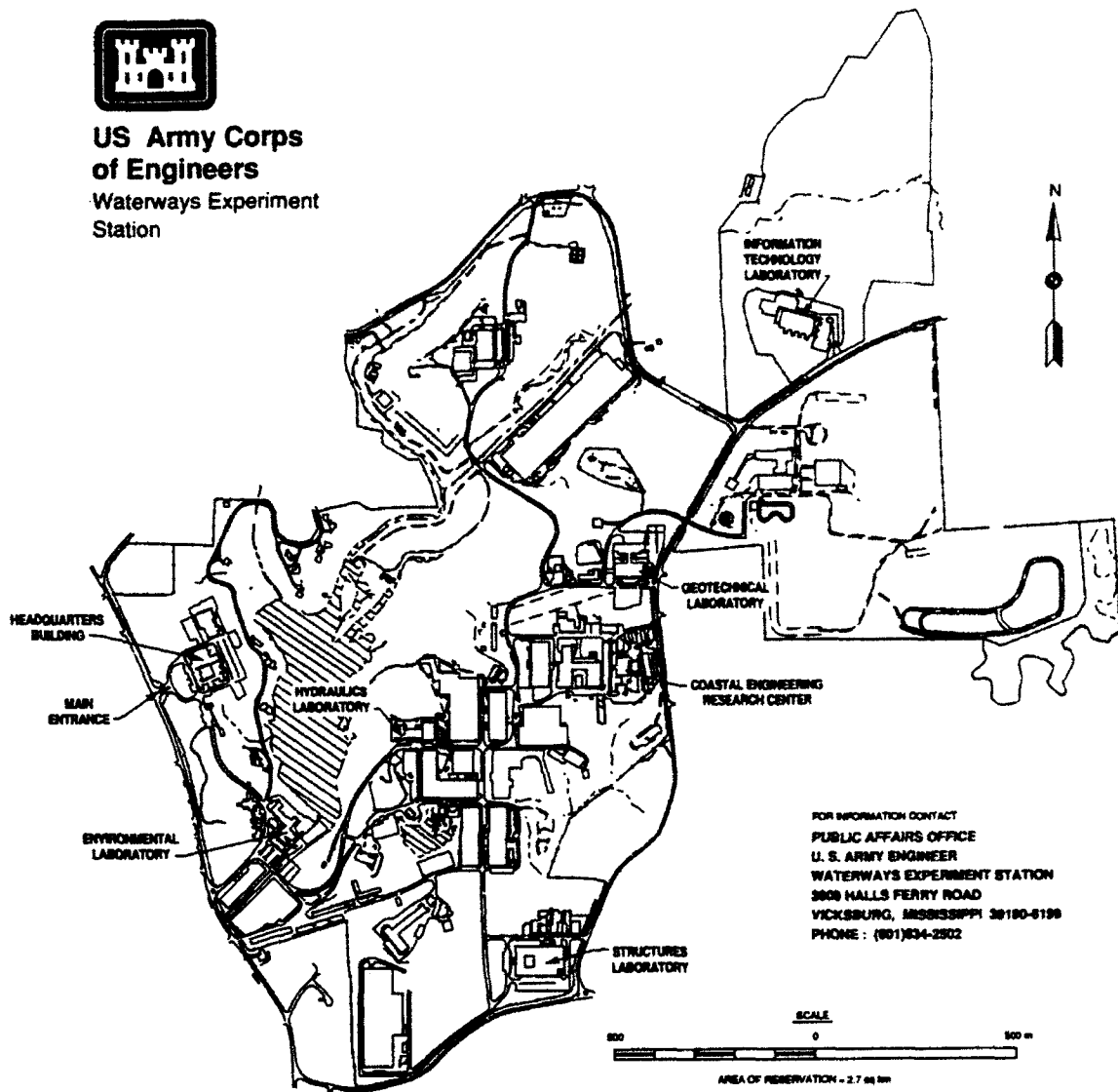3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

US Army Corps of Engineers
Waterways Experiment Station

TABLE OF CONTENTS

TABLES

iv

FIGURES

FIGURES (Continued)

PREFACE

CONVERSION FACTORS, NON-SI TO SI
(METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
feet/sec	0.304878	meters/second
g's (standard free-fall)	9.80665	meters/sec/sec
inches	25.4	millimeters
inches/second	0.025407	meters/second
pounds (force)	4.448	Newtons
pounds (force)/square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms

SECTION 1

INTRODUCTION

1.1 BACKGROUND.

Over the past several years, the Defense Nuclear Agency has funded the Explosion Effects Division (EED) of the USAE Waterways Experiment Station (WES) to develop a large-bore (4-ft[1] diameter) vertical gas gun. The primary purpose of the gas gun is to simulate ground shock environments suitable for testing ground shock measurement devices. A potential, but as yet unexplored, secondary purpose for the gun is to provide dynamic material properties data from relatively large geologic samples.

Gas guns are used to generate localized shock environments in materials, for shock physics studies, by high-velocity impacts of a projectile against samples of the materials under study. A gas gun's ability to produce controlled and repeatable shock inputs is an attractive alternative to high explosive techniques, which are more commonly used to test the performance of ground shock transducers. Typically, gas guns accelerate projectiles which are small (6-in dia. or less) and achieve high velocities. Small gun bores, however, limit the suitability of existing gas guns to test transducers in soils, since they cannot produce the large one-dimensional fields that are desirable for such tests. The purpose of the large-bore gun, recently constructed by WES, is to generate these large, one-dimensional stress and motion fields in different types of soils. These fields can then be used for controlled tests of ground shock transducers, as well as for other shock physics studies.

Some of the desired attributes of the 4-ft diameter gun are that it:

- requires no explosive
- produces repeatable inputs

---

[1]A table of factors for converting non-SI units of measurement to SI (metric) units in presented on page viii.

1

- provides an efficient and cost-effective resting method
- generates minimal noise levels (allowing use in relatively inhabited areas)
- has a vertical orientation (for easier testing)

1.2 DESCRIPTION OF 4-FT DIAMETER VERTICAL GAS GUN.

The gun was designed over a 24-month period beginning in 1988 (Ohrt, (1988), White, (1990a), White (1990b)). An artist's rendering of the 4-ft diameter gas gun is shown in Figure 1-1, and a schematic of the gun is shown in Figure 1-2. The gun consists of a large annular pressure vessel surrounding a vertical barrel. A series of orifices are machined in the barrel wall. These allow the compressed air from the vessel to expand into the barrel. When the gun is in the cocked position, a projectile, with o-rings placed at the top and bottom, straddles the orifices, and prevents the compressed air from being released into the barrel. The projectile is held in place by a quick-release trigger mechanism. A water reaction mass fills the top portion of the barrel above the trigger mechanism. The bottom of the barrel may be sealed with a diaphragm to allow a partial vacuum to be created in the barrel section below the projectile.

To fire the gun, the projectile is released. The weight of the projectile causes it to move downward. As the top o-ring clears the orifices, the compressed air expands into the barrel. The incoming air simultaneously drives the projectile downward and the water reaction mass upward. Theoretically, the mass of the water can be adjusted so that the "bottom" of the mass of water will exit the top of the barrel at the same time that the projectile clears the bottom of the barrel.

To prove that this working concept for a 4-ft diameter vertical gas gun was feasible, a 12-in. diameter vertical gas gun was first designed, built (Joachim (1985), White (1988)), and tested (Ohrt and Welch (1989)). The results of the dynamic and static tests conducted with the 12-in. gun indicated that the 4-ft gun concept was both feasible and practical. Details on the design of each gun and the testing of the 12-in. gun, are given in White, et al (1991).

2

WATER REACTION MASS

PRESSURE VESSEL
HOLDS 300 PSI
COMPRESSED AIR

O-RING SEALS

PROJECTILE

BARREL

VACUUM

4.33"

2"

14.5"

6.2"

PREPARED SOIL TEST
BED WITH INSTRUMENTS
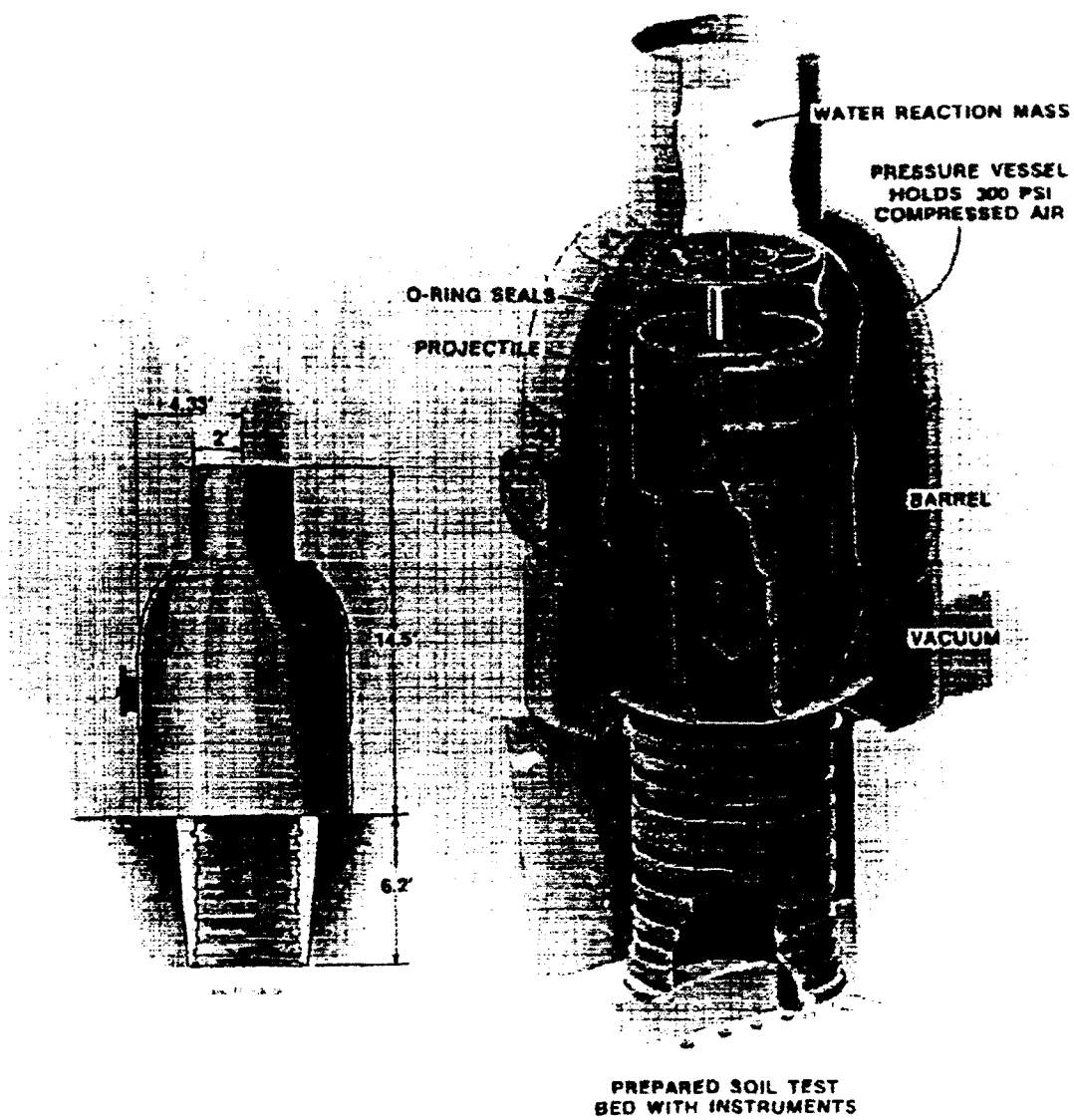
Figure 1-1. WES 4-ft Diameter Vertical Gas Gun.

3
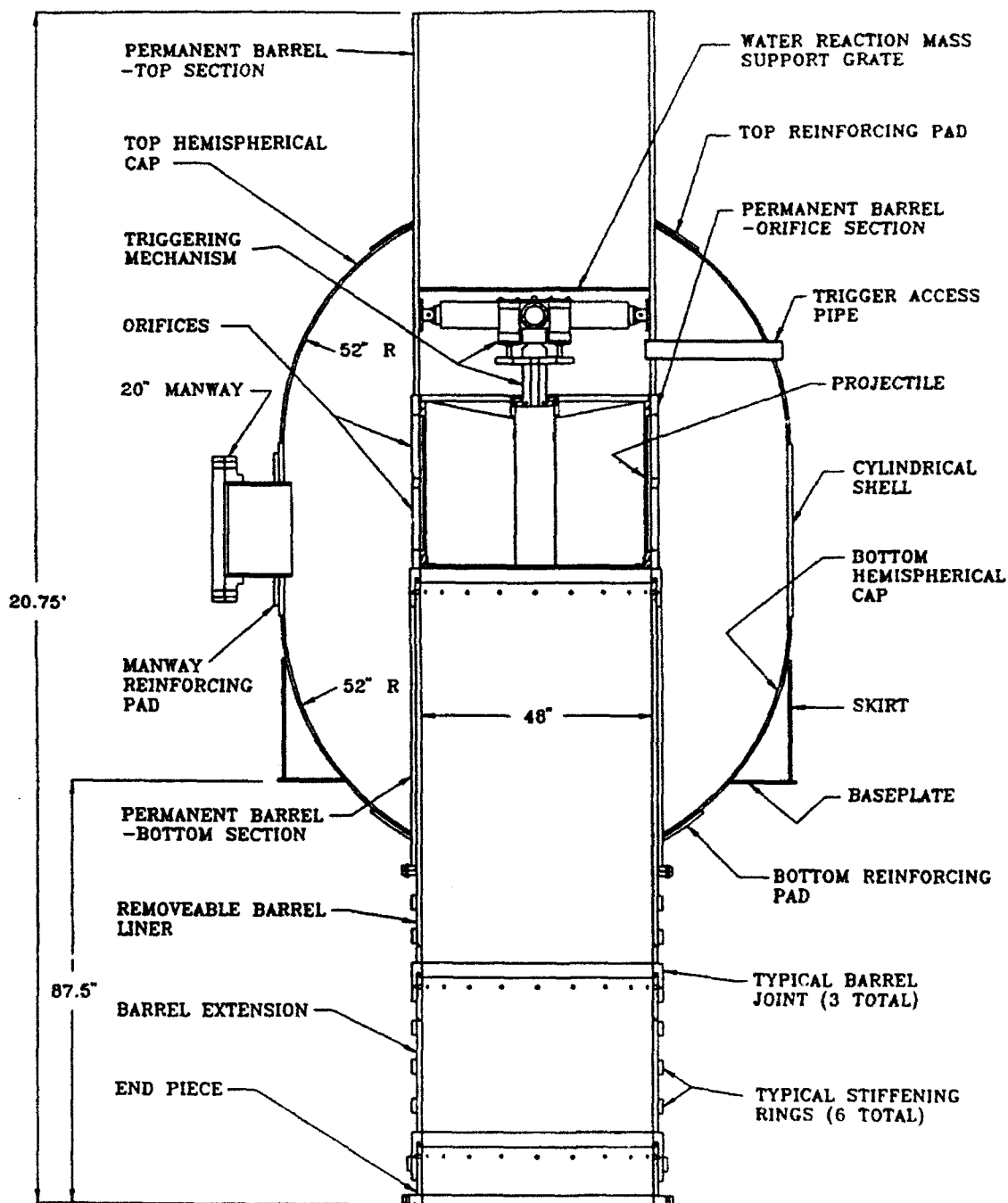
Figure 1-2. Schematic of the 4-ft diameter gas gun.

4

1.3 SCOP

This report presents a discussion of the safety tests conducted on the gun. Comparisons between predicted and measured far field nuisance effects (ground motion and noise) are presented. Also presented is a mathematical model that provides upper bound estimates for the performance of the 4-ft diameter gas gun, i.e., the projectile velocity as a function of the driving vessel pressure. The projectile velocity measured on several pressurized tests with the gun are compared to the predicted values. Conclusions are drawn on the results of the development program to date.

SECTION 2

SAFETY TESTING

2.1 HYDROSTATIC TESTING.

Hydrostatic testing (White, 1990c) was performed to ensure the structural integrity of the pressure vessel and the projectile o-ring seals before placing the 4-ft gas gun in service. The initial phase of hydrostatic testing was conducted immediately following the construction of the projectile. The second phase was conducted to increase the operating level to the maximum design level of 2,070 kPa (300 psi).

Figure 2-1 illustrates the test set-up for both the initial hydrostatic tests and vacuum tests (described later). The gun was oriented horizontally for the initial tests. At the top of the pressure vessel, two high-pressure female couplings were attached, one as a fill line and the other as a bleed line. An additional coupling was attached at the bottom of the tank for draining the water after the hydrostatic tests were completed. These three holes are used during normal operation of the gas gun for filling the tank with air, attaching a relief valve, and attaching a pressure gage.

For the hydrostatic tests, the vessel was first filled with water. Compressed air was then applied to the water-filled tank. The only air in the system was that in the hose connecting the compressor to the gun. The o-ring material used for sealing around the projectile for the first hydrostatic test was a 70-durometer nitrile compound with a 19-mm (3/4-in.) diameter. Testing revealed that this o-ring was inadequate for sealing around the projectile. The failure was a result of several lacerations in the o-ring, created while loading the projectile. As the o-ring moved along the orifices in the barrel, it extruded into the orifices, and was nicked when it passed beyond the top of the orifices.

The second hydrostatic test in the initial series used 16-mm (5/8-in.) diameter o-rings (70 durometer nitrile) in place of the 19-mm (3/4-in.) projectile o-rings. The smaller thickness o-ring extruded less into the orifices, and prevented damage to the o-ring. The vessel was

6
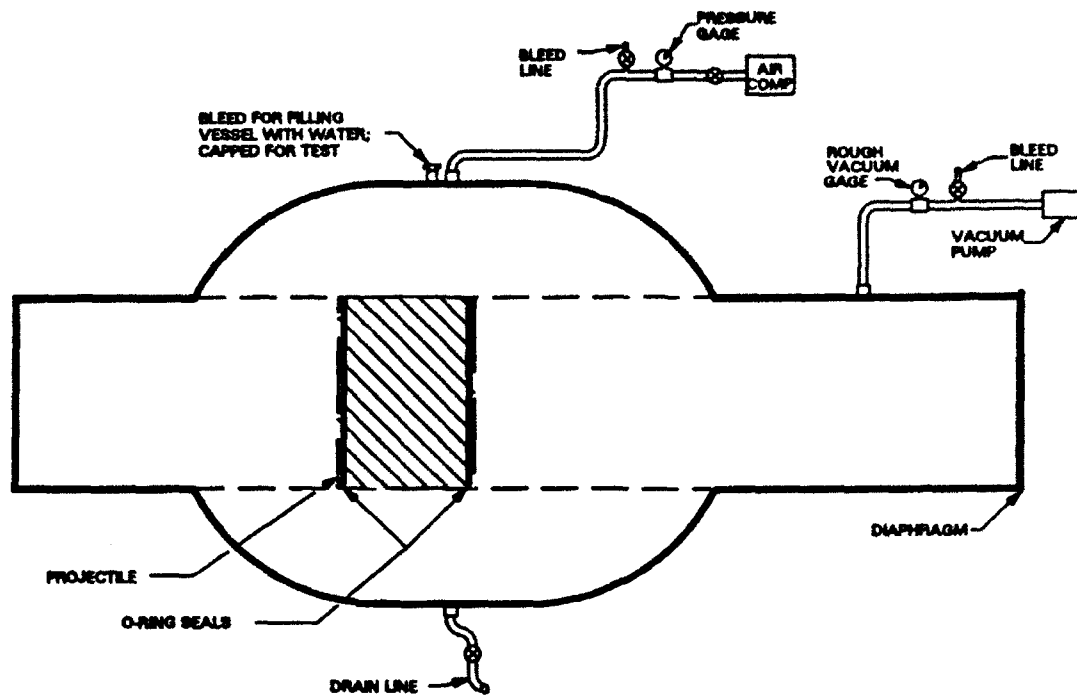
Figure 2-1. Test setup for initial hydrostatic and vacuum testing
of the 4-ft diameter gas gun.

then pressurized to 2,275 kPa (330 psi). The 16-mm o-ring adequately
sealed around the projectile. In addition, the welds of the pressure
vessel were determined to be sound, verifying the structural integrity of
the vessel for conducting tests using pressurized air up to 1,520 kPa
(220 psi). A third hydrostatic test, identical to the second test,
verified these results.

A second series of hydrostatic tests was performed to increase the
operating level of the gun up to its maximum design limit of 2,070 kPa
(300 psi). These tests were conducted after the gun had been placed in
use and tested with air up to pressures of 1,380 kPa (200 psi). The set-
up for the second series of hydrostatic tests is shown in Figure 2-2.
The gun was in its normal testing orientation (vertical) for these tests.
The holes in the vessel that are normally used for filling the tank with
air, for attachment of a relief valve, and for attachment of a pressure
gage, were plugged with high-pressure fittings. Two additional holes
were cut into the vessel; one at the top for filling the vessel with
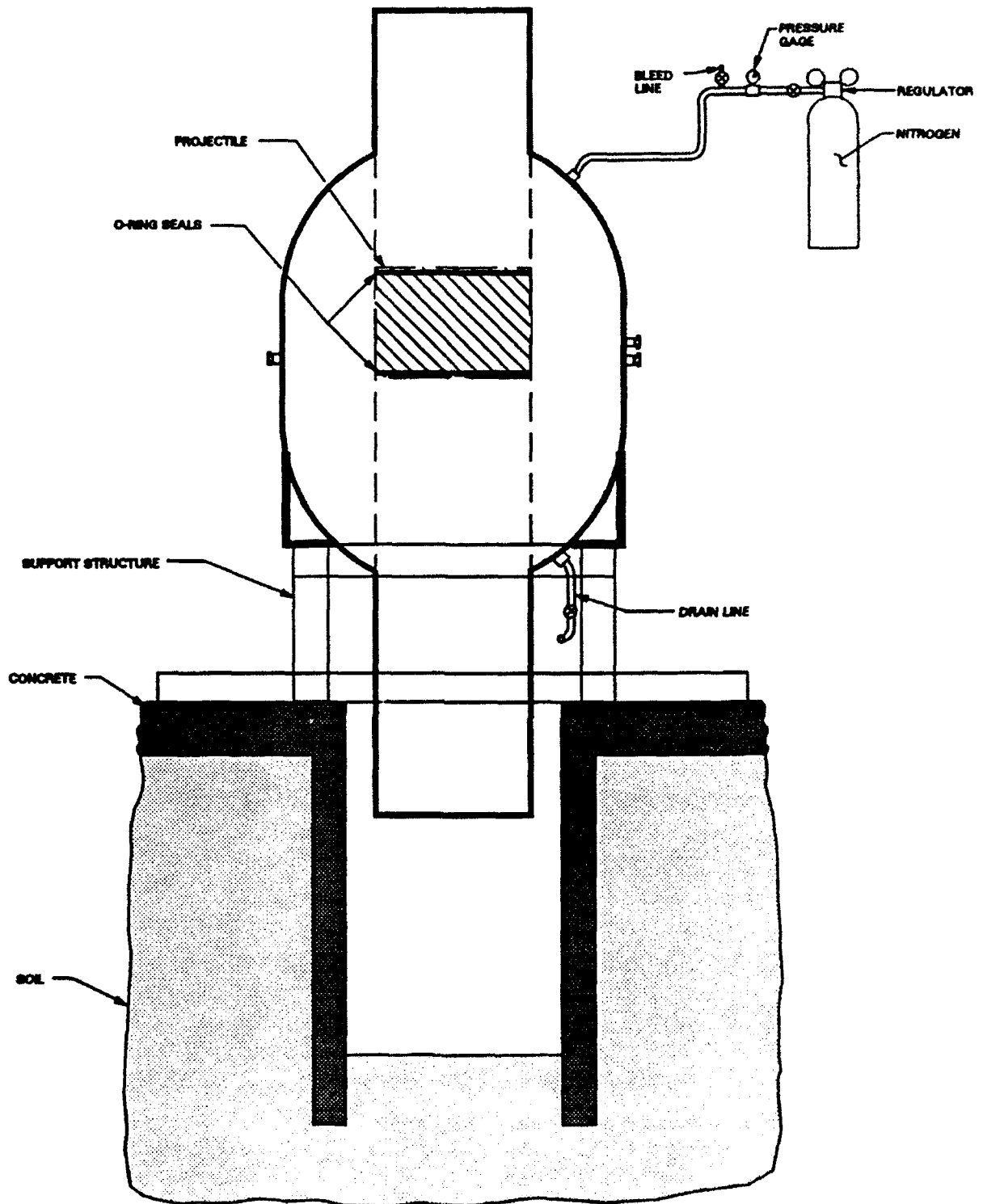
Figure 2-2. Test setup high-pressure hydrostatic testing of
the 4-ft diameter gas gun.

water; and another at the base for draining. As with the previous successful hydrostatic test, 16-mm o-rings were used to seal around the projectile.

After filling the vessel with water, nitrogen was used to increase pressure within the pressure vessel. The pressure was raised to 3,100 kPa (450 psi) using a pressure regulator to control the flow of nitrogen into the vessel. A minimal loss of pressure within the vessel was noted after several minutes at the 3,100 kPa (450 psi) level. The test was repeated to verify the results.

Under existing Army Corps of Engineers safety regulations, tests can be conducted with the gas gun using pressurized air at the maximum design limit of the gun (2,070 kPa, 300 psi); i.e., two-thirds of the hydrostatic test pressure.

2.2 VACUUM TESTING.

Vacuum testing (White, 1990c) was performed by evacuating the barrel of the gas gun beneath the projectile. The purpose of these tests was to evaluate (a) the performance of the o-ring seals on the barrel, (b) the candidate diaphragm material used for sealing the end of the barrel, and (c) the ability of the trigger mechanism to support the vacuum load on the projectile.

The first vacuum test used 19-mm (3/4-in.) diameter o-rings, made from 70-durometer nitrile material, for sealing around the projectile. A diaphragm of 1-mm (0.040-in.)-thick fiberglass reinforced polyester sealed the bottom end of the barrel. After running the vacuum pump approximately 135 seconds, the diaphragm failed at a vacuum level of roughly 460 mm of mercury (Hg).

As of result of the failure of the 1-mm fiberglass reinforced polyester, a second test was conducted using a 12.7-mm (1/2-in.) aluminum plate over the end of the barrel. This test used projectile o-rings made from 16-mm (5/8-in.) diameter, 70-durometer nitrile material. During this test, the vacuum pump was run intermittently while observing both the vacuum gage and the deflection of the diaphragm. The sealing capability of the gun was assessed by observing the loss of vacuum while

9

the pump was off. Approximately 25 mm Hg (3 percent vacuum) was lost during a two-minute span. The rate of loss was fairly constant over the entire range of vacuum.

In order to determine the time required to pull a "full" vacuum, a third test was conducted during which the pump ran continuously, except for brief stops for taking vacuum level readings. The maximum attainable vacuum was approximately 740 mm Hg, which was achieved in 15 minutes. After running the pump for 40 minutes, no change in the vacuum level was evident. The pump is capable of pulling down to a vacuum pressure of 10 microns (759.958 mm Hg), but there are sufficient leaks in the system that prohibit pulling a vacuum greater than approximately 740 mm Hg.

The rate of loss of vacuum (12.5 mm Hg min) was determined to be acceptable. It is not a requirement to hold a vacuum for an extended period of time. Because of the displacement capability of the vacuum pump, it is possible to simply cycle the pump on and off just prior to firing the gun to obtain the desired vacuum level, up to 740 mm Hg. Also, a full vacuum is not required to fire the gun (the projectile will begin moving within the barrel under its own weight, once released by the trigger mechanism).

Also observed on the vacuum test was movement of the projectile. The manner in which the quick-release trigger mechanism is constructed (Figure 2-3) allows for a slight backward rocking motion of the three supporting latches when they are in the cocked position and not carrying a load. The pretest placement of the projectile was such that the latches of the trigger mechanism were not loaded. Posttest, the latches were tight against the retaining collar and could not be rocked backward, indicating that the trigger mechanism was indeed loaded by the vacuum. In future tests, the only loading on the trigger mechanism (in addition to the vacuum) will be the weight of the projectile, which is relatively small when compared to the vacuum loading; i.e., 14,500 N (3,260 lbs) as compared to 155,600 N (26,000 lbs).

The vacuum tests were considered successful. The critical components of the trigger mechanism were tested and found to perform

10

SUPPORTING
CROSSMEMBERS

AIR CYLINDER
(4)

RETAINING COLLAR

LATCH HOUSING

LATCH
(3)

INNER
PROJECTILE PIPE
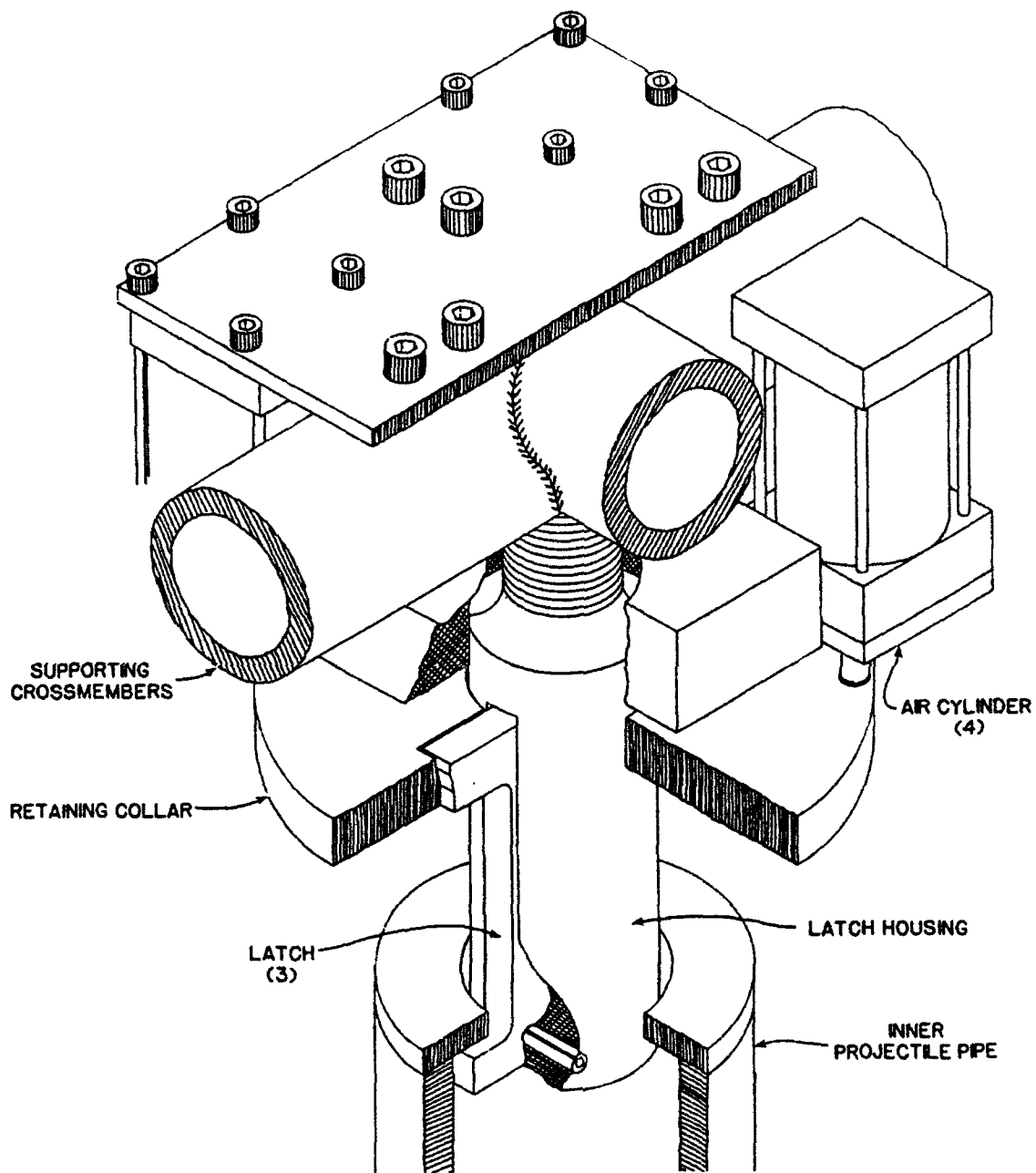
Figure 2-3. Schematic of the trigger mechanism for the gas gun.

11

satisfactorily. In addition, the sealing capability of the o-rings within the gun was found to be adequate.

2.3 SAFETY FEATURES AND SAFETY PLAN.

Safety issues have received the highest priority in the development of the 4-ft diameter gas gun. Some of the safety features included in the design and siting of the gas gun are:

a. <u>Pressure Vessel</u>. The pressure vessel is designed for a maximum working pressure of 2,070 kPa (300 psi). This design includes a minimum factor of safety of four in all components. A manway is incorporated to provide entry to the vessel for periodic inspection. A relief valve is attached to the vessel to prevent overpressurizing.

b. <u>Trigger Mechanism</u>. A "potential energy" well has been incorporated into the design of the trigger mechanism (Figure 2-3) used to fire the gas gun. The mating surface of the latch and the retaining collar of the trigger mechanism is designed such that, when the retaining collar is lifted vertically, the latch must rotate into its housing. This rotation slightly lifts the projectile prior to firing. Requiring the application of a significant force in this manner in order to fire the gun greatly reduces the chance of a misfire.

c. <u>Operation Controls</u>. The controls for operation of the gas gun (Figure 2-4) are located away from the immediate vicinity of the gun. These controls operate the "fill system" used in conducting a gas gun test. The fill system (illustrated in Figure 2-5) is comprised of three components; the pressure system, the vacuum system, and the firing system. The pressure and vacuum systems incorporate valves to bleed off the pressure in the vessel and the vacuum in the barrel, should a test be aborted, or in the event of a misfire. Also included in the control panel is a master switch that prevents firing the gun until all fill system components are in their proper state; i.e., all valves closed and the air compressor and vacuum pump are shut off. The Standard Operating Procedure (SOP) for conducting a test is posted on the control panel in plain view of the operator.

12
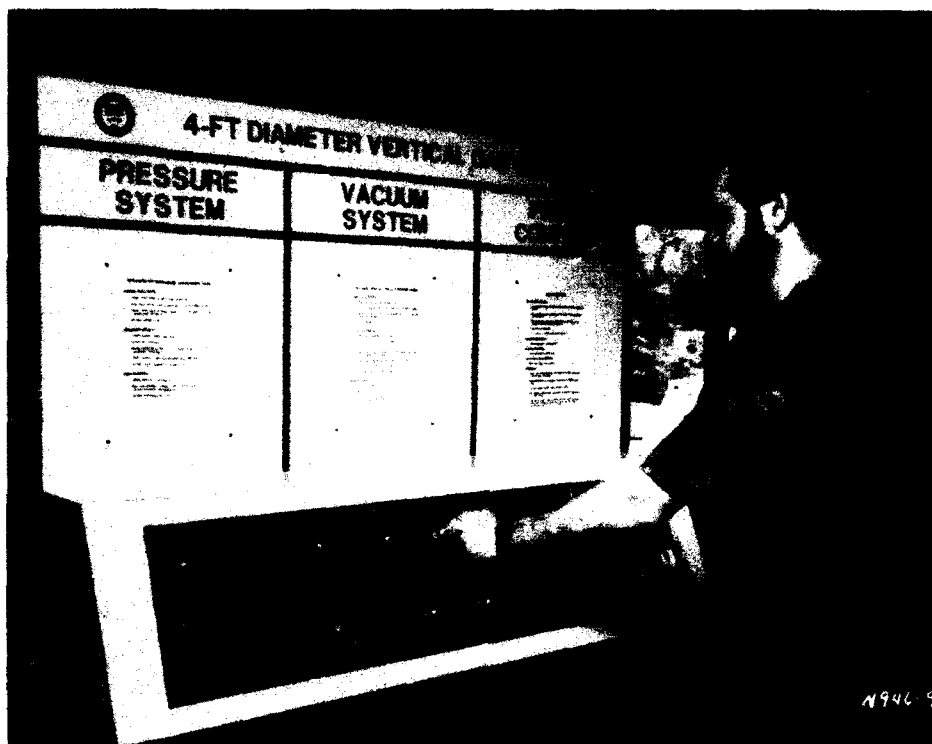
Figure 2-4. Control panel used in operating the gas gun.

d. **Location of Gas Gun**. The gas gun is situated over a trench 2.1 m (7 ft) deep and 8.5 m (28 ft) long. Steps located at one end of the trench and a ladder at the other provide access into and out of the trench. The Engineering and Construction Services Division at WES was consulted to ensure that the shoring in the trench, handrails along the steps, and railing along the side of the trench comply with the US Army Corps of Engineers Safety and Health Requirements Manual, EM 385-1-1.

e. **Test Plan**. A cautious and conservatively safe plan was followed for the preliminary testing of the gun. The plan called for initial testing with atmospheric vessel pressure, followed by tests with gradual increases in vessel pressure. The performance of various gun components (barrel, projectile, instrumentation, etc.) were carefully evaluated after each test.

A Safety Plan/Standard Operating Procedure (SOP) was developed for the 4-ft diameter gas gun (Appendix B). Its purpose is to provide a

13
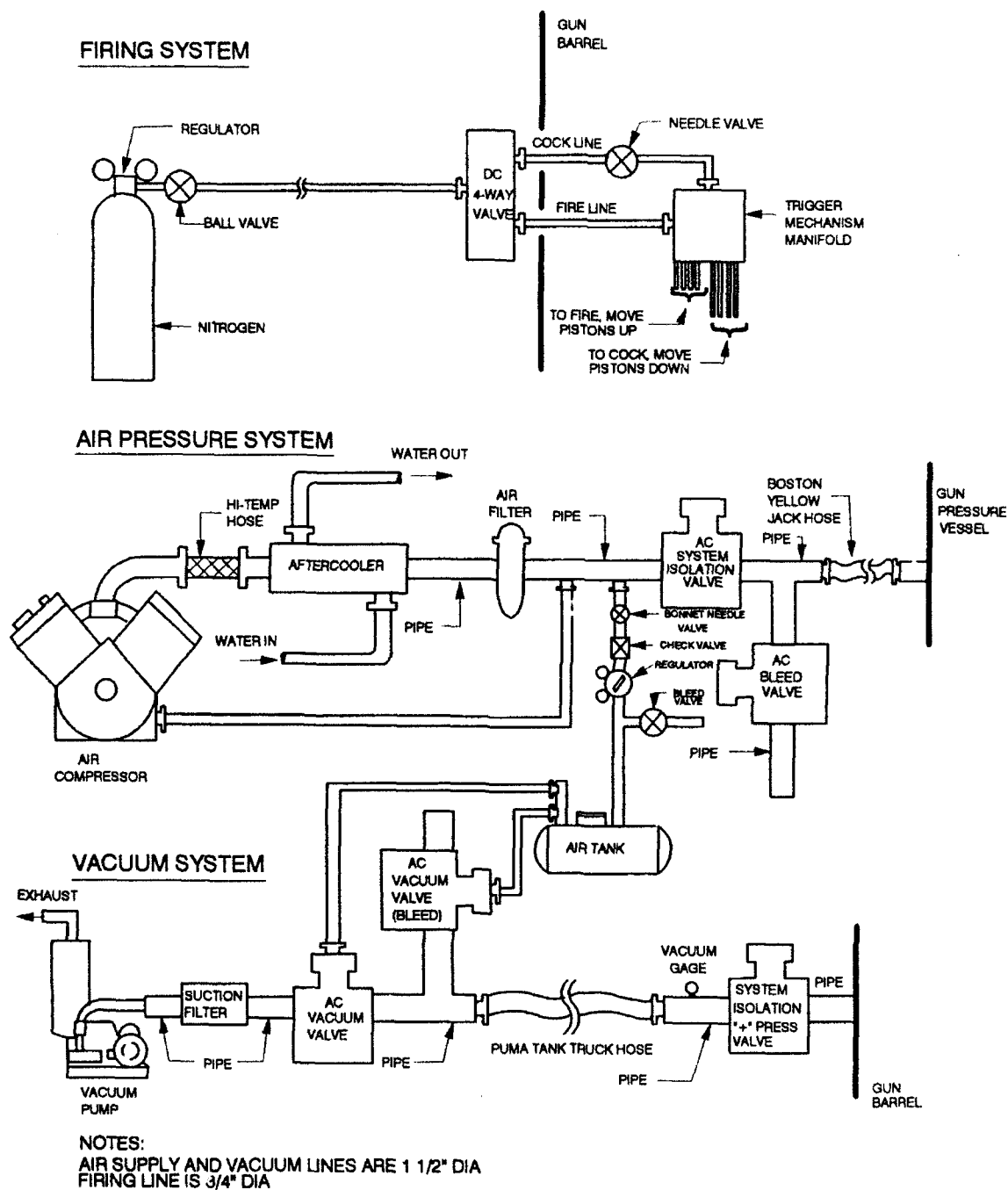
Figure 2-5. Fill system used for conducting tests with the gas gun.

14

systematic method of conducting tests in a safe manner. The plan prescribes the safety policies and procedures for testing with the gas gun and applies to all personnel participating on a test. The requirements listed below were mandatory for all gas gun tests.

a. The Standard Operating Procedure is followed when conducting a test.

b. All components of the gun are inspected on a regular basis.

c. When the projectile was in the loaded position between tests, the battery power to the four-way directional valve (used for firing the gun) is disconnected. Two safety chains are used to secure the projectile's position within the barrel between tests.

d. No personnel are allowed in close proximity (53 m (175 ft)) to the gun when a test is being conducted.

e. A warning horn is sounded one minute prior to firing the gun. A second warning is sounded thirty seconds prior to firing the gun. Three short blasts are sounded to count down the final seconds prior to firing.

f. A manned road block is placed at the entrance of the service road to the test site prior to presurizing the vessel.

g. A standard procedure for reentering the test site is followed. As a minimum, this procedure includes a visual inspection of the concrete pads, the platform supporting the gun, and the trench shoring.

h. A pump is maintained on-site to remove any water in the trench.

15

SECTION 3

NUISANCE EFFECTS: PREDICTIONS AND MEASUREMENTS

There was no experience base available for estimating the probable range of nuisance effects associated with the operation of a gas gun as large as the WES 4-ft diameter gun. Accordingly, an asessment had to be made of the potential nuisance-level noise and far-field ground motions that would be generated by the operation of the gun. This assessment included the development of upper bound predictive equations for the induced far-field ground motion, and careful monitoring of the induced noise and far-field ground motions, during the test to insure that these quantities were within acceptable limits. Predictive equations and far-field data gathered during the tests are presented in the following sections.

3.1 GROUND MOTION.

In order to evaluate potential hazards to buildings in the vicinity of the 4-ft gas gun, calculations of far-field ground motions were performed for various projectile impact velocities.

Wallace and Fowler (1973) developed a relationship for peak vertical particle velocity as a function of range from the impacts of spheres dropped onto soil surfaces from a given height. The equations convert the kinetic energy of the sphere's impact into an equivalent-explosion energy yield for TNT explosives. This relationship is

$$V_i = 15240\left(\frac{E}{R^3}\right)^{1/2} \tag{3.1}$$

where,

V_i = peak vertical particle velocity for impacts (mm/sec)

E = yield energy (lbs of TNT)

R = range from the impact or explosion point (ft)

By determining the explosion energy yield, in pounds of TNT, equivalent to the kinetic energy of the 4-ft gas gun projectile at the time of impact, the far-field motions can be predicted.

16

Figure 3-1 shows the predicted upper bound impact velocity (as a function of vessel pressure) for a 1,478 kg (3,260 lb) projectile. In this calculation, adiabatic expansion of the air is assumed, and the mass of the air and friction between the projectile and the barrel walls is ignored. A detailed development of the mathematical model used to predict projectile impact velocity is presented in Section 4.

The kinetic energy, KE (N-m), of the projectile at the time of impact is given by

$$KE = \frac{1}{2} M_P V_P^2 \qquad (3.2)$$

where,

M_p — projectile mass (kg)

V_p — projectile impact velocity (m/sec)

Substituting Equation (3.2) into Equation (3.1), and using a TNT equivalence of 1.912×10^6 N-m/lb-TNT yields

$$V_i = 15240 \sqrt{\frac{M_P V_P^2}{2R^3 (1.912 \times 10^6)}} \qquad (3.3)$$

where,

V_i — peak vertical particle velocity (mm/sec)

R — range from the detonation (ft)

The computer code PARTVEL (listed in Appendix C) was written using Equation (3.3) to calculate the peak vertical particle velocity for projectile velocities between 0 and 90 m/sec (295 ft/sec) for various ranges of interest. The ranges of interest are listed in Table 3-1.

17
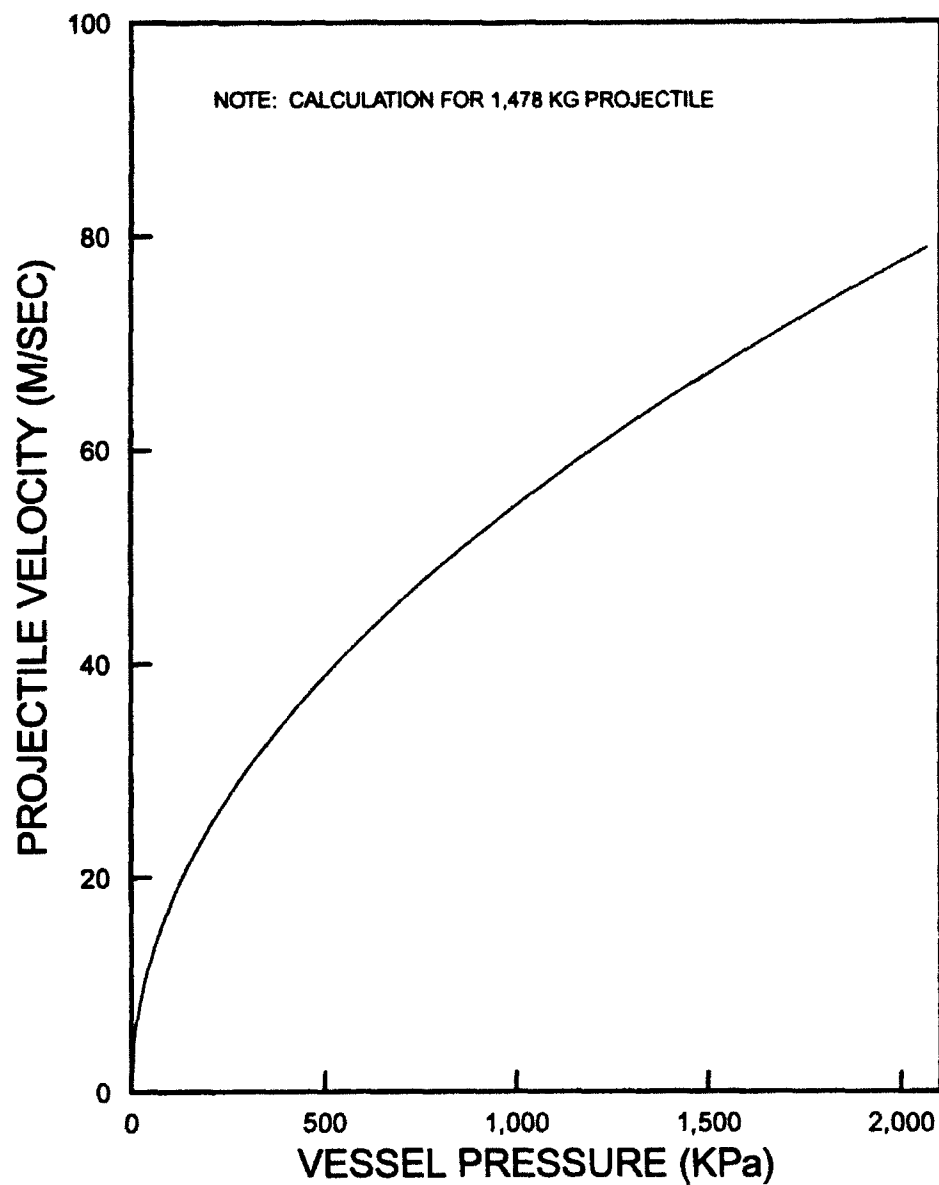
Figure 3-1.   Predicted velocity for a 1,478-kg (3,260-lb) projectile.

18

Table 3-1. Ranges of interest for testing with the 4-ft gun.	
Location	Range, m (ft)
Nearest (uninhabited) bldg	9 (30)
Control Trailer, location of nearest personnel	53 (175)
Nearest inhabited WES bldg, not associated with testing	78 (255)
Guard at entrance road to site	100 (325)
Nearest residential bldg (outside station boundary)	233 (765)

The threshold of human perception of ground vibration is significantly lower than the levels associated with the onset of structural damage. Subjective human response to vibratory ground motion, based on earthquake studies, has shown that motions of 0.1 mm/sec amplitude are the absolute lower limit of human perception, and amplitudes of less than 1 mm/sec are rarely perceived for short-period, explosion-produced motions (Ristvet, 1987). Ristvet lists a level of 20.3 mm/sec as "unpleasant," and Siskind, et al (1990) gives 17.8 mm/sec as the level of "discomfort," or producing a "startle" effect. Siskind also lists thresholds of 56 mm/sec and 112 mm/sec for an onset of interference with activity or proficiency, and a health limit, respectively.

Peak particle velocity is usually taken as the significant parameter in the development of damage criteria for structures. Listed in Table 3-2 is a summary of damage thresholds for residential structures, taken from several references. In general, these criteria state that no structural damage should occur below a peak particle velocity of 50 mm/sec.

The results of PARTVEL calculations for the 9-m (30-ft) range are shown in Figure 3-2. Though this prediction indicates that a building at

19

Table 3-2. Structural damage thresholds from references.			
Damage Type	**Particle Velocity Damage Threshold**		
	Langefors, et al (1958)	Nicholls, et al (1971)	McPherson (1989)
None	< 71 mm/sec (2.8 in./sec)	< 50 mm/sec (2.0 in./sec)	< 50 mm/sec (2.0 in./sec)
Fine plaster cracks	109 mm/sec (4.3 in./sec)	50-100 mm/sec (2-4 in./sec)	-
Plaster and masonry wall cracking/ minor structure	160 mm/sec (6.3 in./sec)	100-178 mm/sec (4-7 in./sec)	137 mm/sec (5.4 in./sec)
Major structural damage/ serious cracking	231 mm/sec (9.1 in./sec)	> 178 mm/sec (7 in./sec)	193 mm/sec (7.6 in./sec)

this range could incur structural damage when testing with projectile velocities greater than 27 m/sec (90 ft/sec), no damage to the storage building, located at the 9-m range, was noticed after testing at even the highest projectile velocities.

Shown in Figure 3-3 are the predicted peak vertical particle velocities as a function of projectile velocity for the remaining ranges of interest. Triaxial motion measurements (vertical, radial and tangential) were made at three far-field ranges on several tests with the gas gun. These ranges were 53 m, 78 m, and 233 m. The peak value of the three measurements, at a given range, for a single gas gun test is shown in Figure 3-3. This data is tabulated in Table 3-3. Note that, at the nearest residential building outside the WES boundary (233 m), the measured values of ground motion are two orders of magnitude less than that level typically regarded as a hazard to residential structures. At the location of the nearest personnel (the control trailer at 53 m), the levels are a factor of five lower than the allowable threshold (50 mm/sec, or 2 in./sec). Personnel located at the 53-, 78-, and 100-m ranges could feel the impact for most projectile velocities.

20
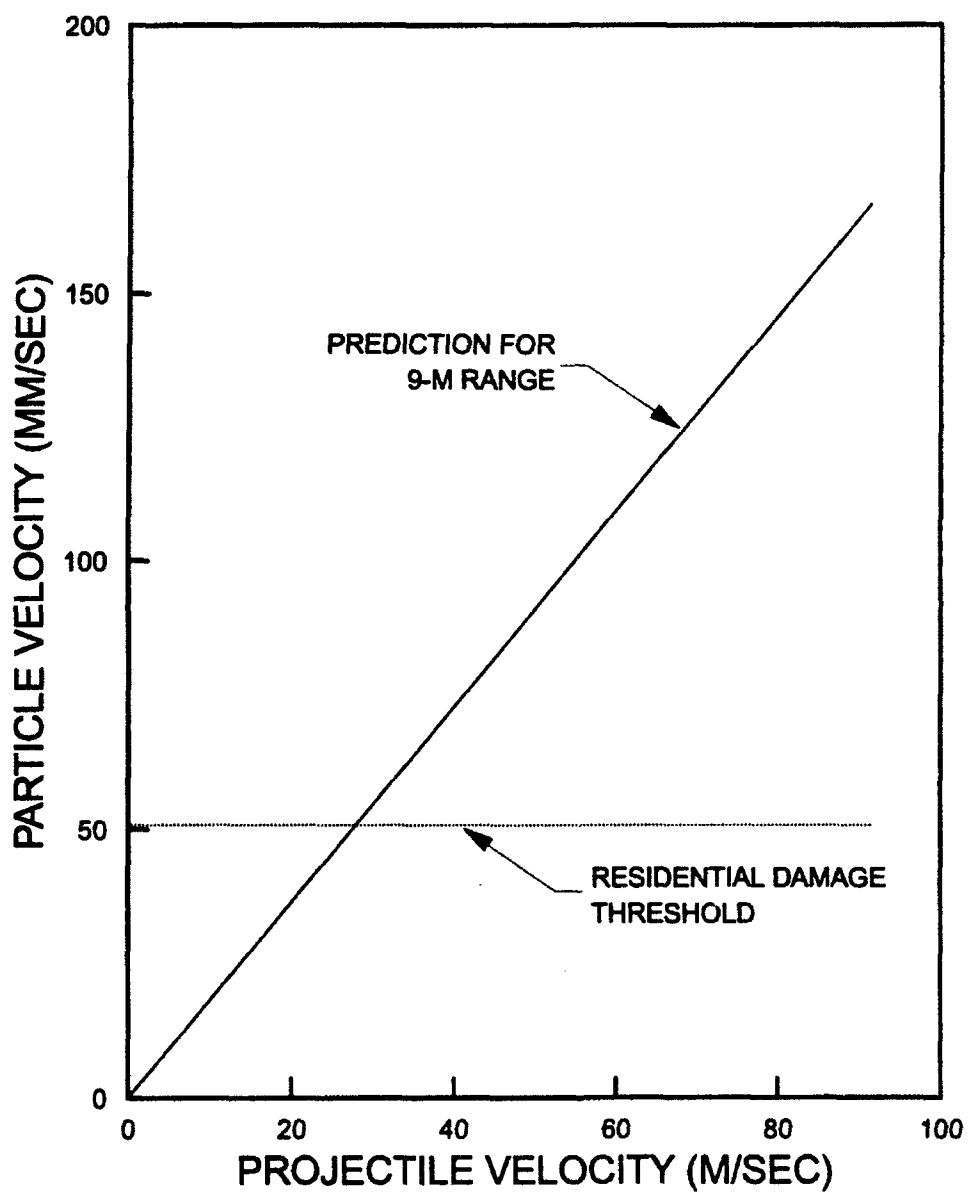
Figure 3-2. Predicted peak particle velocity as a function of
projectile velocity for the 9-m (30-ft) range.
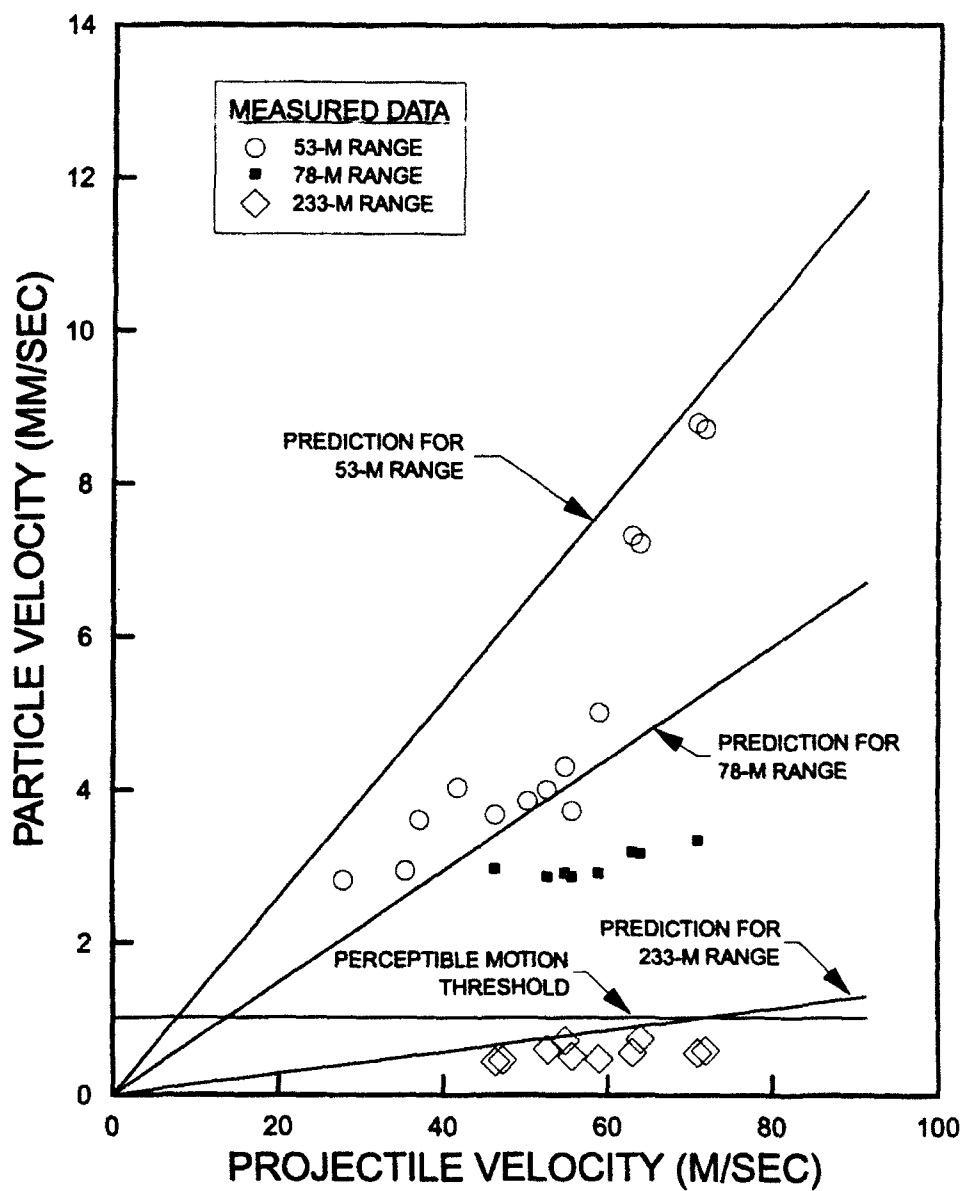
Figure 3-3. Predicted peak particle velocity as a function of
projectile velocity for various far-field ranges.

Table 3-3. Sound pressure level, far-field velocity, and airblast data from WES 4-ft Diameter Vertical Gas Gun tests.

TEST NO	TEST LEVEL (kPa)	PROJECTILE VELOCITY (m/sec)	SOUND PRESSURE LEVEL (dB)					FAR FIELD DATA MAX VELOCITY† (mm/sec), MAX PRESSURE (Pa)					
			9 m RANGE	53 m RANGE	78 m RANGE	100 m RANGE	233 m RANGE	53 m RANGE		78 m RANGE		233 m RANGE	
								VEL	PRES	VEL	PRES	VEL	PRES
3	159	32.0*	135.0	114.5	101.5	112.5	105.5	2.7R	20.7	NF	NF	ND	ND
4	345	ND	137.0	116.0	110.0	102.5	105.5	3.7R	200.0	NF	NF	ND	ND
5	0	5.4	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
6	345	27.9	126.5	107.5	106.5	116.0	108.0	2.8R	6.9	NF	NF	NF	NF
7	517	37.1	131.0	113.5	106.5	103.0	111.5	3.6R	NF	NF	NF	NF	NF
8	517	35.5	ND	113.5	111.0	103.0	ND	2.9R	NF	NF	NF	NF	NF
9	690	ND	134.0	ND	ND	106.0	100.5	4.3R	NF	NF	NF	0.5R	ND
10	862	47.2	ND	121.0	ND	111.0	109.0	ND	ND	NF	NF	0.4T	16.5
11	1,014	50.3	ND	118.0	ND	ND	106.0	3.9R	ND	NF	NF	ND	ND
12	662	41.8	132.0	114.0	104.5	111.0	104.5	4.0R	NF	NF	NF	NF	NF
13	1,027	52.7*	143.5	129.0	128.5	NF	112.0	4.0V	248.3	2.9V	82.7	0.6R	25.5
14	1,207	55.7	ND	126.5	NF	ND	ND	3.7V	227.6	2.9V	75.9	0.5R	24.1
15	1,379	59.0	NF	NF	NF	118.5	112.5	5.0R	275.9	2.9V	62.7	0.5R	31.7

† Max velocity from vertical (v), radial (R), or tangential (T) component
* Velocity based on one set of TOA pins
** 88% of predicted value
ND = No Data
NF = Not Fielded

23

Table 3-3. Sound pressure level, far-field velocity, and airblast data from WES 4-ft Diameter Vertical Gas Gun tests. (Continued)

TEST NO	PROJECTILE VELOCITY (m/sec)	SOUND PRESSURE LEVEL (dB)					FAR FIELD DATA MAX VELOCITY† (mm/sec), MAX PRESSURE (Pa)					
		9 m RANGE	53 m RANGE	78 RANGE	100 m RANGE	233 m RANGE	53 m RANGE		78 m RANGE		233 m RANGE	
							VEL	PRES	VEL	PRES	VEL	PRES
16	ND (46.3**)	NF	NF	NF	NF	110.0	3.7v	137.9	3.0v	71.7	0.4R	25.5
17	ND (54.9**)	NF	123.0	NF	NF	109.5	4.3v	225.5	2.9v	59.3	0.7R	27.6
18	64.0	NF	127.0	126.0	NF	113.5	7.2R	639.2	3.2v	ND	0.7v	113.8
19	63.0	NF	125.5	126.5	NF	116.5	7.3R	337.9	3.2v	1,538	0.6v	32.4
20	ND (72.0**)	NF	127.5	129.5	NF	117.0	8.7R	213.7	ND	1,145	0.6R	32.4
21	71.0	NF	127.5	127.5	NF	116.0	8.8R	213.7	3.4v	903	0.6v	26.2
22	46.8	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF

24

The calculations presented in Figures 3-2 and 3-3 do not consider the topography of the area, which perhaps accounts for the discrepancy between predicted and measured values. The elevation of the gun is 50.3 m (165.1 ft). An embankment adjacent to the gun rises to an elevation of 54.9 m (180 ft) before dropping to 41.6 m (136.6 ft) at Durden Creek, some 143 m (470 ft) away. The elevation rises to 57.7 m (189.2 ft) at the nearest residential structure located outside of the WES boundary. These severe changes in grade that exist between the gun and locations of interest apparently aided in attenuating the ground shock.

3.2 AIRBLAST.

During a gas gun test, the pressurized air driving the projectile and reaction mass will vent at both the top and bottom of the barrel. This pressure release into the atmosphere will cause an airblast wave in the vicinity of the gas gun. Personnel in the area will sense the airblast wave by hearing it, and if close enough, by feeling it. In order to evaluate potential hazards to personnel (hearing damage) and buildings (window breakage), calculations were performed to predict the airblast/nuisance levels from testing with the gun. Sound pressure level measurements were made during several tests at all five ranges of interest (see Table 3-1). In addition, measurements of airblast were made at three far-field ranges (53, 78, and 233 m) on several tests.

Sound pressure level data gathered during tests with the WES 12-in diameter vertical gas gun was used to predict the airblast level, for the ranges of interest, when testing with the 4-ft gun. The noise level associated with the airblast at these ranges was then determined.

During the performance evaluation tests of the 12-in gun, sound pressure level measurements were made at the 9- and 33.5-m ranges for several different vessel pressures. This data is presented in Figure 3-4. Note from this figure that, with the exception of the two measurements made at the 33.5-m (110-ft) range for a vessel pressure of 345 kPa (50 psi), the data is relatively constant for a given range. Therefore, an average value of the sound pressure level (using all data

25
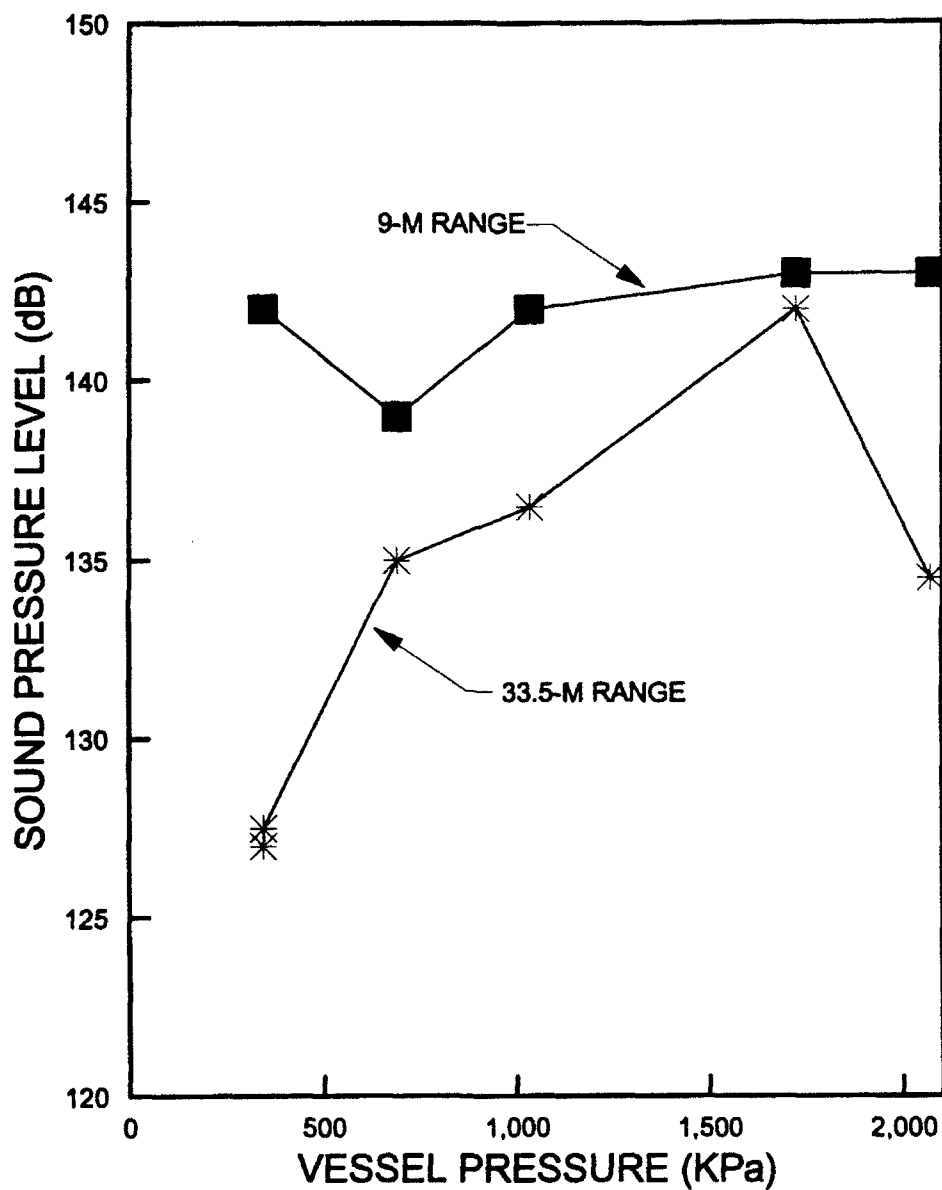
Figure 3-4. Sound pressure level measurements made when testing with the WES 12-in. Diameter Vertical Gas Gun.

points) was determined for each range. The peak airblast pressure amplitude associated with a given sound pressure level measurement may be determined from the relations (Kinsler, et al, 1982)

$$P = \sqrt{2}\, P_e \qquad (3.4)$$

and

$$SPL = 20 LOG\left(\frac{P_e}{P_{ref}}\right) \qquad (3.5)$$

where,

P — peak pressure amplitude

P_e — effective pressure

P_{ref} — reference pressure (20 ιPa)

SPL — sound pressure level (dB)

Solving for P_e in Equation (3.5) and substituting into Equation (3.4) yields the peak pressure amplitude, P (in Pascals):

$$P = \sqrt{2}\, P_{ref} 10^{\left(\frac{SPL}{20}\right)} \qquad (3.6)$$

Substituting the average value of the SPL data for the 12-in gun into Equation (3.6) yields the peak pressure amplitude at the two ranges.

In order to use the 12-in. gun data for predicting the peak pressure amplitude at various ranges of interest for the 4-ft gun, each range was normalized by dividing by the gun diameter (11.5 in.). The results of Equation (3.6) for the 12-in. gun data are tabulated as a function of the normalized range in Table 3-4 and presented graphically in Figure 3-5. Listed in the Table 3-5 are the peak pressure amplitude and SPL predictions (scaled from the linear fit to the 12-in. gun data presented in Figure 3-5) at the ranges of interest for the 4-ft gun. The ranges are also expressed in normalized values (range/gun diameter).

27

Table 3-4. Airblast/nuisance data for the 12-in gun.			
Range m (ft)	Normalized Range	Peak Pressure Pa (psi)	Avg. SPL dB
9 (30)	31	348 (0.05)	141.8
33.5 (110)	115	137 (0.02)	133.7

Table 3-5. Predicted airblast/nuisance data for the 4-ft gun.			
Range m (ft)	Normalized Range	Peak Pressure Pa (psi)	SPL dB
9 (30)	7.5	931 (0.135)	150.3
53 (175)	43.75	269 (0.039)	139.6
78 (255)	63.75	207 (0.030)	137.3
100 (325)	81.25	176 (0.0255)	135.9
233 (765)	171.25	105 (0.0152)	131.4

The sound pressure level corresponding to the scaled values of pressure for the 4-ft gun may be determined by solving for P_e in Equation (3.4) and substituting into Equation (3.5).

$$SPL = 20LOG\left(\frac{P}{\sqrt{2}\,(20E\text{-}6)}\right) \tag{3.7}$$

where P has units of Pa and SPL has units of dB. By substituting the scaled peak pressure amplitudes for the 4-ft gun into Equation (3.7), the predicted SPL's can be tabulated (Table 3-5) and presented graphically (Figure 3-6).

OSHA regulations state that exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level. This threshold is included in Figure 3-6 for comparison to predicted and measured noise levels at the various ranges of interest for testing with the 4-ft gun. For the 4-ft gun, the 9-m range is the only one of concern that lies above the 140 dB limit. As mentioned previously, the closest range at which personnel were located during testing was 53 m. As with the ground

28
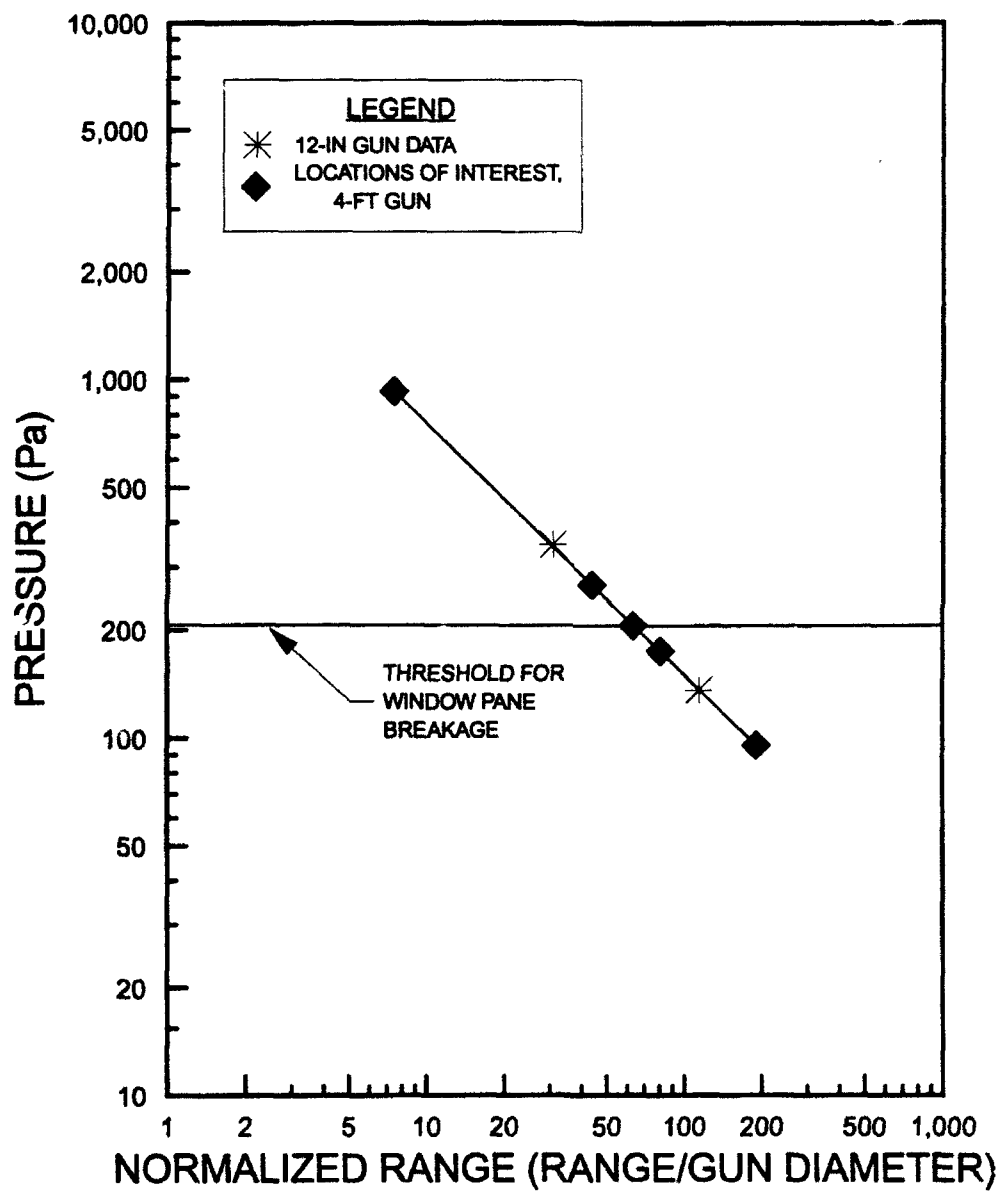
Figure 3-5. Airblast pressure measurements and predictions as a
function of normalized range for gas gun testing.

29
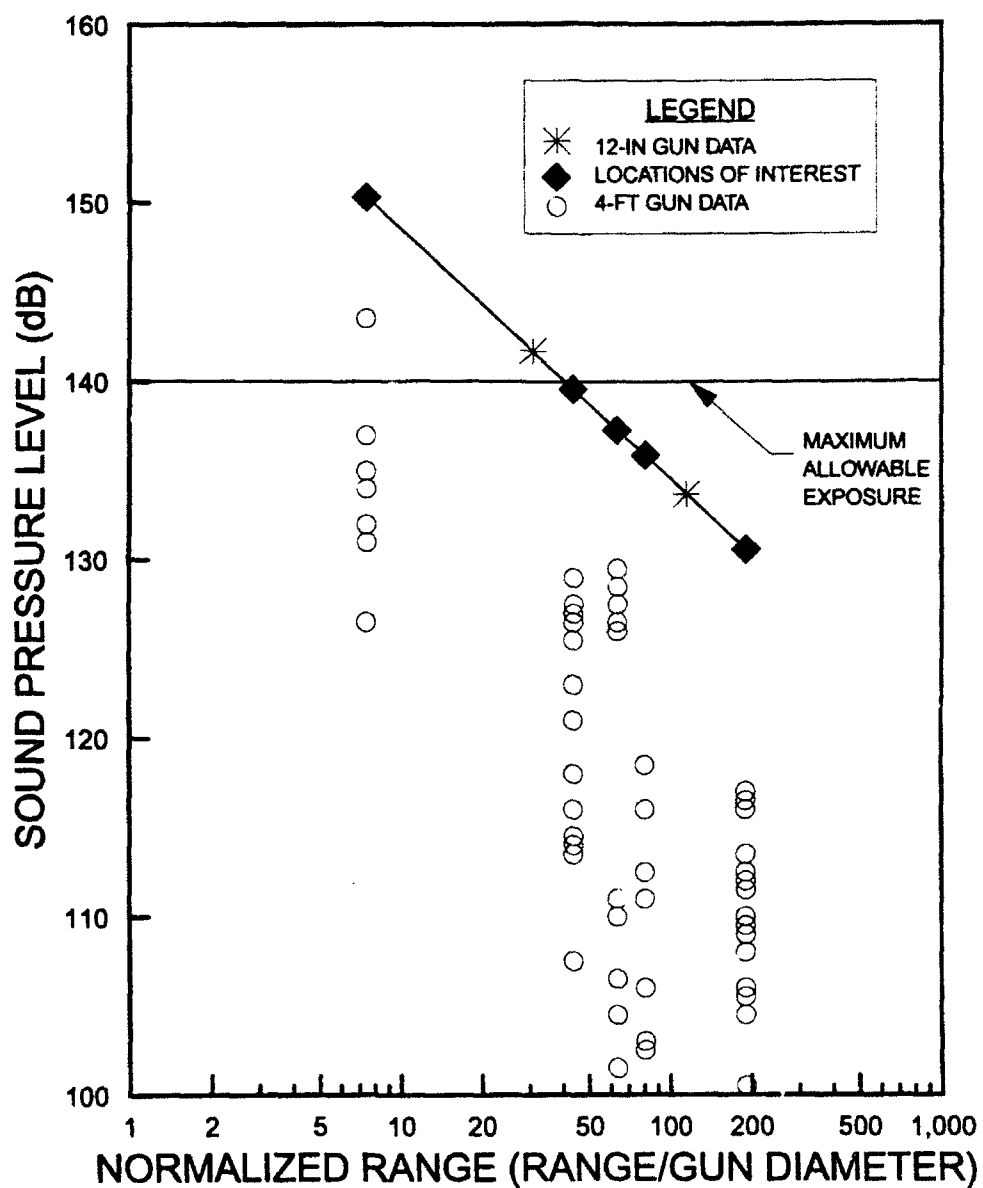
Figure 3-6. Measured and predicted sound pressure levels as a function of normalized range for the 4-ft gas gun tests.

shock calculations, this analysis does not take into account the natural terrain (hills and trees) effects that will tend to mitigate the airblast wave and thus reduce noise levels.

Presented in Figure 3-7 are the sound pressure level data, for the various ranges of interest, as a function of vessel pressure. Note from this figure and Figure 3-6 that, although the measured levels are relatively high, they are well below limits requiring safety precautions (i.e., ear protection). Personnel located approximately 3.2 km (2 miles) from the gun, aware that a test was imminent, heard the gun during tests at the very highest levels; i.e., 1,725 kPa (250 psi) and greater.

The most likely component of an ordinary structure to sustain damage from a blast wave is a window. Therefore most damage criteria are based on window pane breakage. Not all window panes will break at the same blast pressure level, so the study of this phenomena is statistically based. Some large plate glass windows may break at a pressure level of 207 Pa (0.03 psi). At 690 Pa (0.1 psi) some windows break and at 6,900 Pa (1.0 psi) most windows break. At a pressure level of 20.6 kPa (3.0 psi) conventional structures are severely damaged (Blaster's Handbook, 1980). The 207 Pa threshold for window pane damage is included in Figure 3-5. From this figure, or from Table 3-5, it was determined that windows in buildings located at the 9, 53, and 78-m ranges might sustain damage. The probability of window damage cannot be determined from this analysis. However, it is interesting to note that the close-in data point for the 12-in. gun is located above the 207 Pa (0.03 psi) threshold and windows at that range were not damaged during performance testing with the 12-in. gun.

The windows of the building at the 9-m (30-ft) range were covered with a sheet of plywood to prevent possible breakage during a test with the 4-ft gun. No windows were damaged, at any location, during any test with the 4-ft gas gun.

31
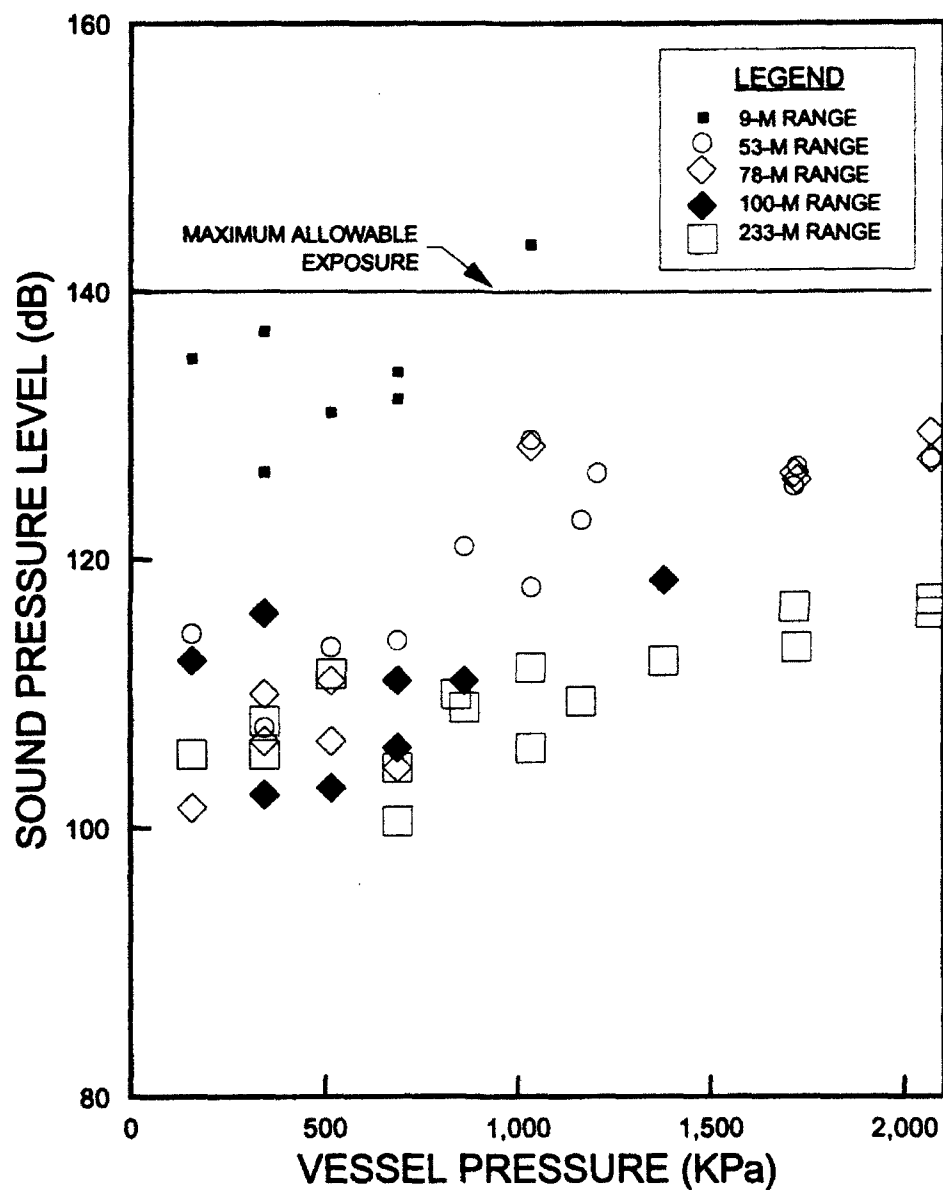
Figure 3-7.   Measured sound pressure levels generated by
              the 4-ft gas gun as a function of vessel
              pressure, for various ranges of interest.

32

SECTION 4

MATHEMATICAL MODEL

A mathematical model of the gas gun operation was formulated by Welch and Ohrt (White, et al (1991)) in order to calculate projectile velocity as a function of initial vessel pressure.

Consider the simplified view of the gas gun shown in Figure 4-1. The dashed lines show the initial positions of the projectile and reaction mass (masses M_p and M_r, respectively). The trigger mechanism and its supporting members are located in the chamber between the two masses. This initial volume is denoted by V_{cham}, and the volume of the pressure vessel by V_{pv}. The area of the barrel is given by A. The displacement of the projectile is given by the variable x and that of the reaction mass is given by the variable y. Hence, the total volume at any time is

$$V = V_{pv} + V_{cham} + A(x+y) \tag{4.1}$$

Let the pressure at any time after firing be P. Since the areas of the projectile and reaction mass are the same, the gas exerts an equal force, $F = PA$, on each. Ignoring frictional forces between the barrel walls and the projectile and reaction masses, Newton's second law produces

$$F = M_p \ddot{x} = M_r \ddot{y}$$

Rearranging and integrating twice yields

$$y = \frac{M_p}{M_r} x \tag{4.2}$$

Substituting Equation (4.2) into Equation (4.1) yields

$$V = V_{pv} + V_{cham} + Ax\left(1 + \frac{M_p}{M_r}\right) \tag{4.3}$$

For a given projectile displacement, x, Equation (4.3) provides the volume of gas, V, of the system. Assuming adiabatic expansion of the gas, the pressure, P, of that volume has the relation

33
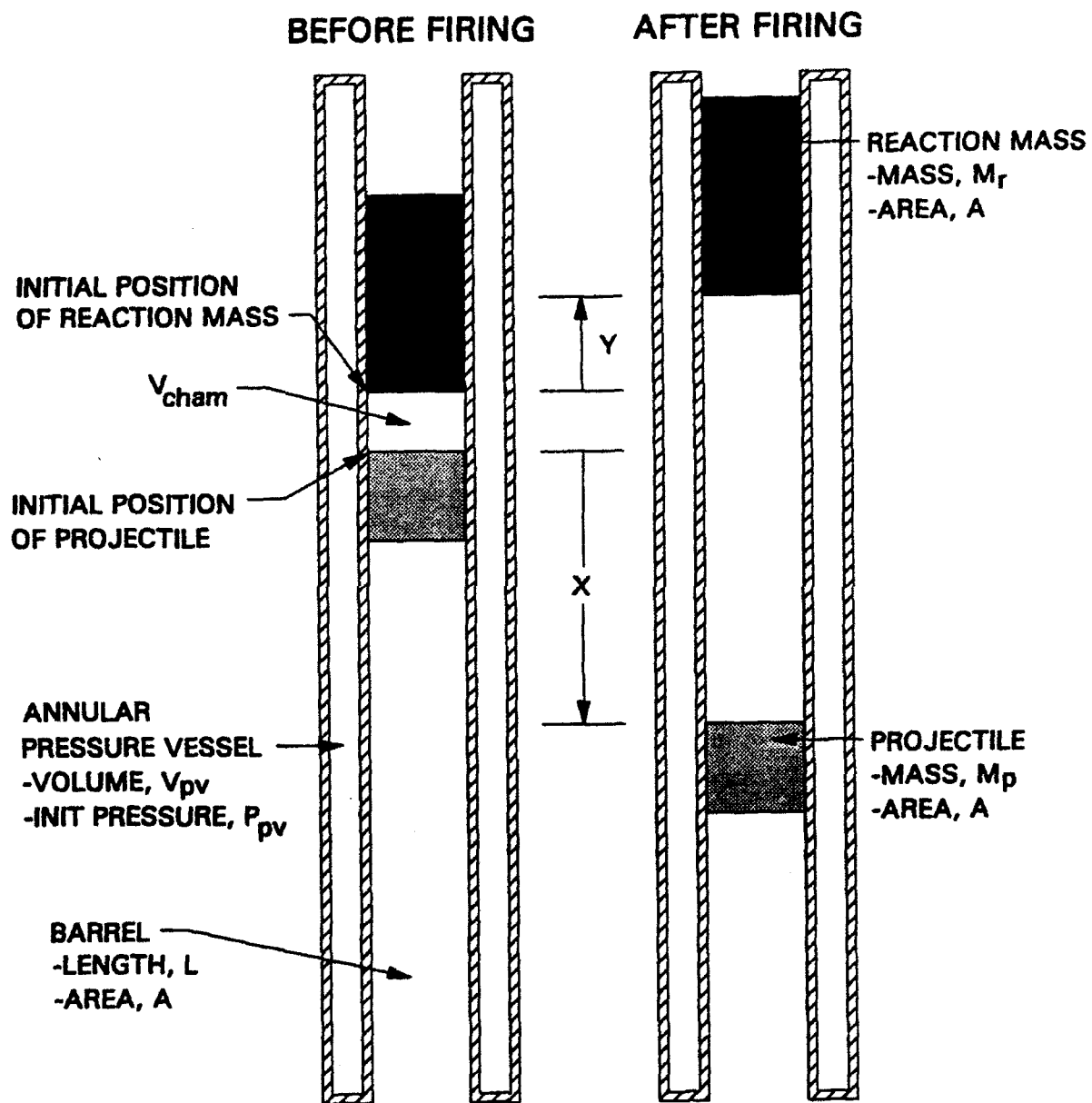
Figure 4-1. Parameters used in developing the mathematical model.

gas, the pressure, P, of that volume has the relation

$$PV^\gamma = constant$$

where γ is the ratio of specific heats for the gas (about 1.4 for air). If the pressure and volume are known at any time, say P_1 and V_1, then the pressure and volume as a function of time is given by,

$$P(t) = \frac{P_1 V_1^{1.4}}{(V(t))^{1.4}} \qquad (4.4)$$

Before the projectile and reaction masses are driven by the gas, the gas must first expand into the chamber between the two masses. The pressure (P_{pv}) and volume (V_{pv}) of the pressure vessel, and the chamber volume (V_{cham}) are known. Using Equation (4.4), the initial pressure acting on the masses can be calculated as

$$P_{init} = \frac{P_{pv} V_{pv}^{1.4}}{(V_{pv} + V_{cham})^{1.4}} \qquad (4.5)$$

The pressure acting on the projectile that produces a given projectile displacement, x, may be found by substituting Equations (4.3) and (4.5) into Equation (4.4),

$$P = P_{init}\left[\frac{V_{pv} + V_{cham}}{V_{pv} + V_{cham} + Ax\left(1 + \frac{M_p}{M_r}\right)}\right]^{1.4} \qquad (4.6)$$

The work done on the projectile by this pressure is given by

$$W = \int dW = \int PdV = \int_0^{L_p} PAdx$$

where L_p is the distance traveled by the projectile. Substituting Equation (4.6) in the last of these expressions yields

$$W = \int_0^{L_p} P_{init}\left[\frac{V_{pv} + V_{cham}}{V_{pv} + V_{cham} + Ax\left(1 + \frac{M_p}{M_r}\right)}\right]^{1.4} Adx \qquad (4.7)$$

After integrating, this expression becomes

35

$$W = \frac{2.5 P_{init}(V_{pv} + V_{cham})}{\left(1 + \frac{M_p}{M_r}\right)} \left[1 - \left(\frac{V_{pv} + V_{cham}}{V_{pv} + V_{cham} + AL_p\left(1 + \frac{M_p}{M_r}\right)}\right)^{0.4}\right] \qquad (4.8)$$

The velocity of the projectile, Vel_p, may be found by equating the work done on the projectile with the kinetic energy of the projectile. This ignores the kinetic energy of the compressed air moving behind the projectile and is an upper bound calculation of the projectile's velocity. Thus,

$$KE = \frac{1}{2} M_p Vel_p^2 = W$$

Substituting Equation (4.8) and solving for Vel_p yields,

$$Vel_p = \sqrt{\frac{5 P_{init}(V_{pv} + V_{cham})}{M_p\left(1 + \frac{M_p}{M_r}\right)} \left[1 - \left(\frac{V_{pv} + V_{cham}}{V_{pv} + V_{cham} + AL\left(1 + \frac{M_p}{M_r}\right)}\right)^{0.4}\right]} \qquad (4.9)$$

Equation (4.9) gives the velocity of the projectile, for a given vessel pressure, after it has travelled a distance L_p. Recall that P_{init} in this equation is given by Equation (4.5). The reaction mass, M_r, is selected using Equation (4.2) by setting the height of the reaction mass equal to the distance it must travel, L_r. The distance the projectile travels before leaving the barrel is L_p; therefore, the travel distance of the reaction mass, L_r, is given by

$$L_r = \frac{M_p}{M_r} L_p \qquad (4.10)$$

But $M_r = AL_r\rho$, where ρ is the density of the reaction mass. Substituting this into Equation (4.10) and rearranging, we have,

$$L_r = \sqrt{\frac{M_p L_p}{A\rho}}$$

Hence,

$$M_r = \sqrt{M_p L_p A \rho} \tag{4.11}$$

The predicted projectile velocity for a 1,478 kg (3,260 lb) projectile, shown in Figure 3-1, was calculated using the computer code GG4PV, listed at Appendix D. This code uses Equations (4.5) and (4.11) in Equation (4.9) to calculate the projectile velocity as a function of vessel pressure. The volume of the pressure vessel, V_{pv}, is constant (10.05 m^3, 355 ft^3) as is the area, A, of the barrel (1.17 m^2, 12.57 ft^2). The mass of the projectile, M_p, the distance traveled by the projectile, L_p, and the chamber volume, V_{chom}, vary depending of the configuration of the projectile. The value for each is typically 1478 kg (3260 lb_m), 3.26 m (10.7 ft), 1.8 m^3 (63.7 ft^3), respectively.

SECTION 5

PERFORMANCE TESTS OF 4-FT GAS GUN

5.1 PROJECTILE CONFIGURATION.

The projectile design currently used in the 4-ft gas gun is shown in Figure 5-1. This design incorporates the initial projectile design (White, 1990b and White, et al, 1991) by using it as a carriage for an impact plate. Improvements to the initial design of the projectile include:

- The thickness of the bottom plate of the carriage was increased
- The thickness of the material used for the stiffening gussets inside the carriage was increased
- The weight-reducing holes in the gussets of the former design were eliminated
- Additional smaller gussets were added inside the carriage
- Closed-cell polyurethane foam was added between the carriage and the impact plate.

The closed-cell polyurethane foam, sandwiched between the bottom plate of the carriage and the impact plate, is used to limit the stress acting on the bottom of the carriage. As testing levels increase (higher vessel pressures and projectile velocities), thicker pieces of foam are required to absorb the impact energy, and thus protect the carriage from damage. Foam thicknesses varied from 10 cm (4 in.) to 30 cm (12 in.) during recent tests with the gun. The mass of the projectile varied very slightly as a result of changing the foam thickness. All tests used the projectile configuration of Figure 5-1. The carriage was not damaged during the test series. Two 5-cm (2-in.) thick impact plates were used during the test series. Other than occasionally stripping out the threaded holes in the impact plate during a test, the plates were not damaged.
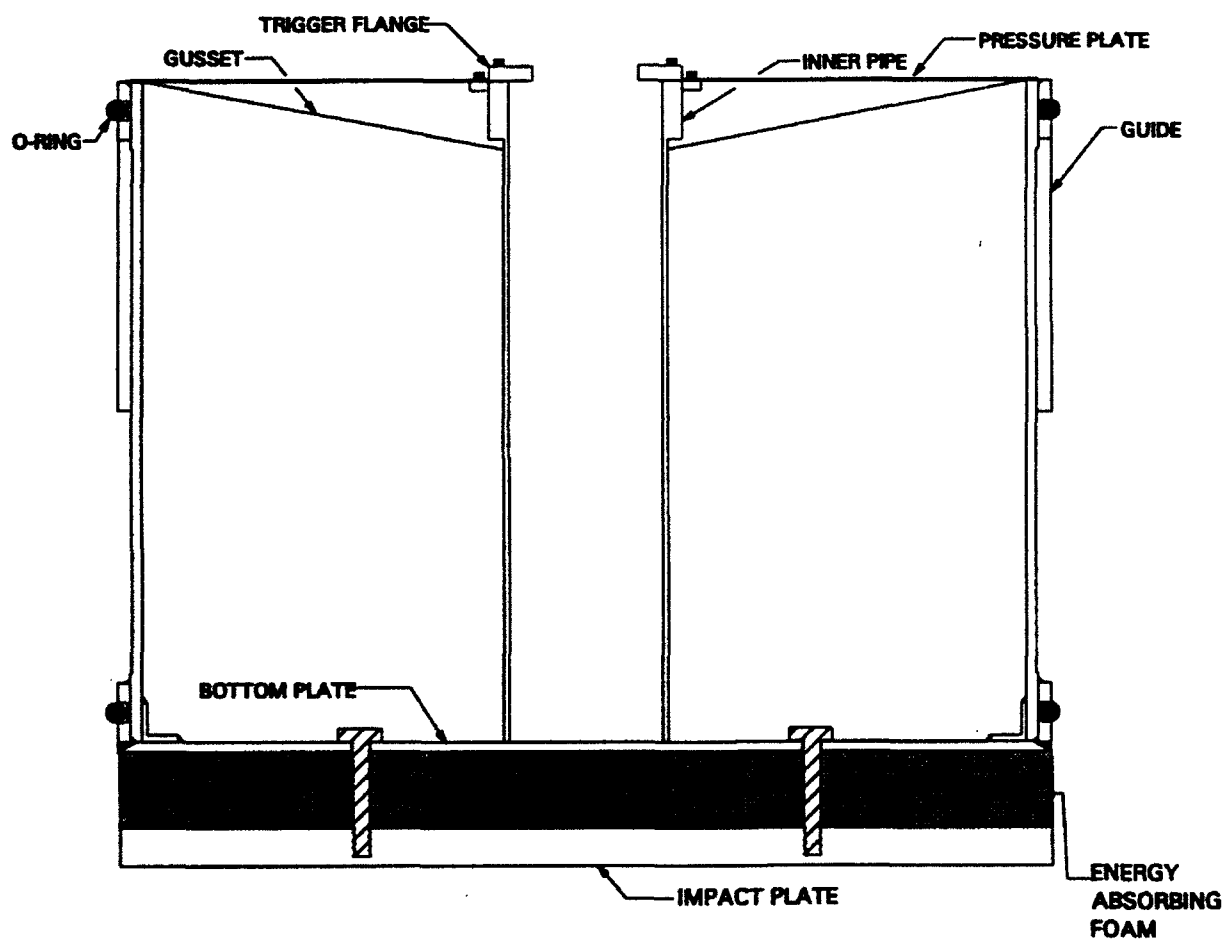
Figure 5-1. Cross section of the gas gun projectile.

5.2 PROJECTILE VELOCITY AND PLANARITY MEASUREMENTS.

Six piezoelectric pins, located at the base of the barrel of the gun, were used to monitor the velocity and planarity of the projectile as it exited the barrel. Shown in Figure 5-2 are a plan view and a section view of the location of the 6 pins. Pins T-1A and T-3A are located 25.4 mm (1 in.) above the plane containing the 4 pins designated T-1B, T-2, T-3B, and T-4. A schematic showing the orientation of the piezoelectric pin within its bushing, and the projectile within the barrel of the gun, is shown in Figure 5-3. A Time-of-Arrival Data System (TOADS) box, running at a clock speed of 1 MHz, was used to record the time-of-arrival (TOA) of the projectile at each pin location. Two measurements of projectile velocity were computed by comparing the TOA of the projectile at the locations T-1A/T-1B and T-3A/T-3B. The planarity of travel of the projectile was computed by comparing the measurements at pin locations T-1B, T-2, T-3B, and T-4.

Several factors determine the accuracy of the velocity/planarity measurements. These include the accuracy of machining the holes in the barrel and the holes in the pin bushing, the flatness of the impact plate, the assembly of the projectile, and the positioning of the pins within the bushing. Considering these factors, the accuracy of the location of each pin was determined to be ± 0.6 mm (0.023 in.). Therefore, the actual distance between two pins used to measure the projectile velocity could be as much as 26.6 mm (1.046 in.) or as little as 24.2 mm (0.954 in.). Hence, the accuracy of the velocity measurement is ± 4.6 percent. Likewise, pins assumed to be located in a common horizontal plane could have a relative difference in their vertical position of 1.2 mm. The tolerance on the planarity measurement depends on the location of the two pins exhibiting the greatest disparity in TOA. For pins located 90° apart the tolerance is ±1.439 milliradians and for pins located 180° apart the tolerance is ±1.018 milliradians. The frequency response of the piezoelectric pin and the recording system is high enough to eliminate any significant contribution to error of these measurements.
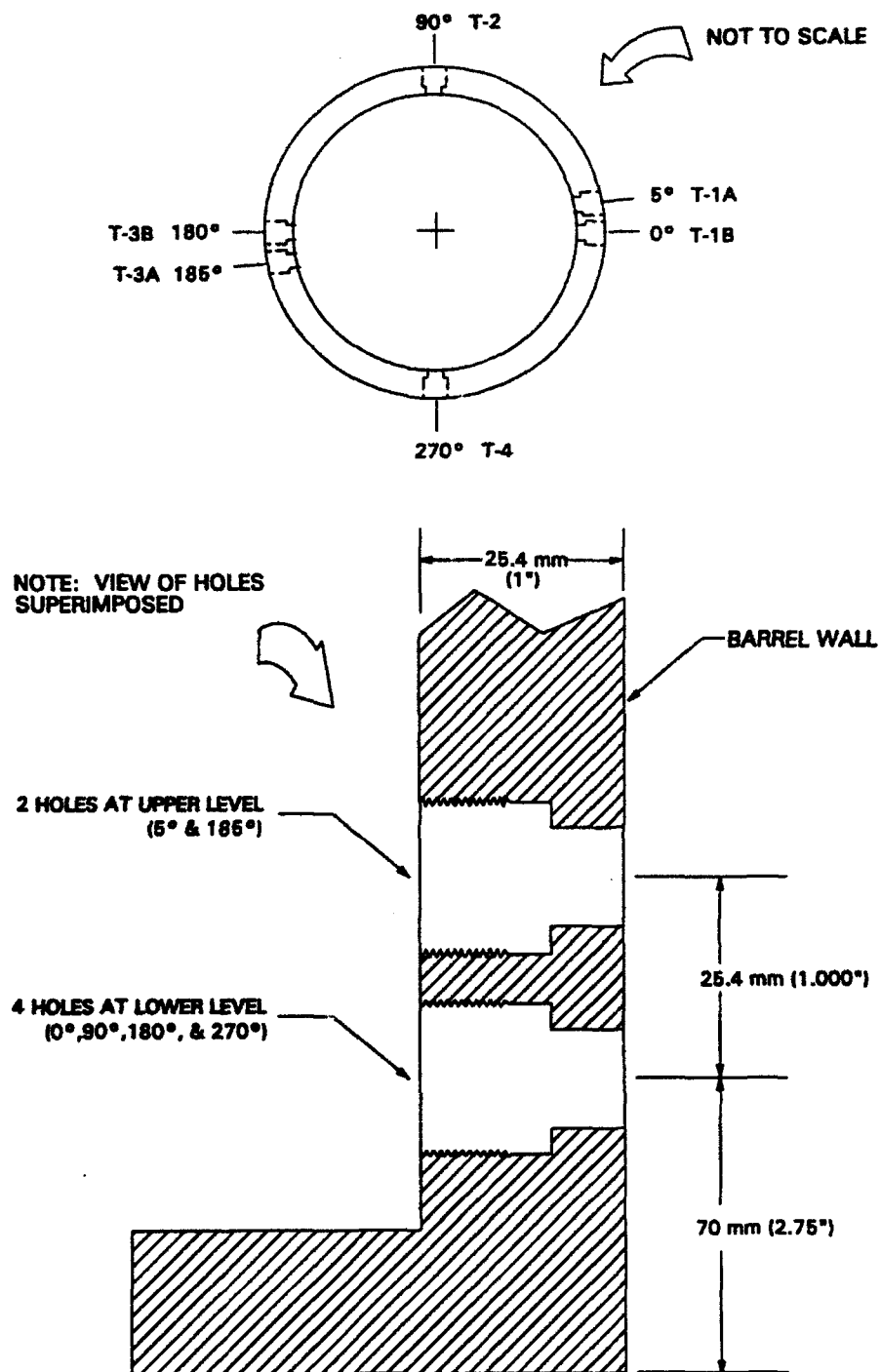
Figure 5-2. Piezoelectric pin locations for velocity and planarity measurements.

41
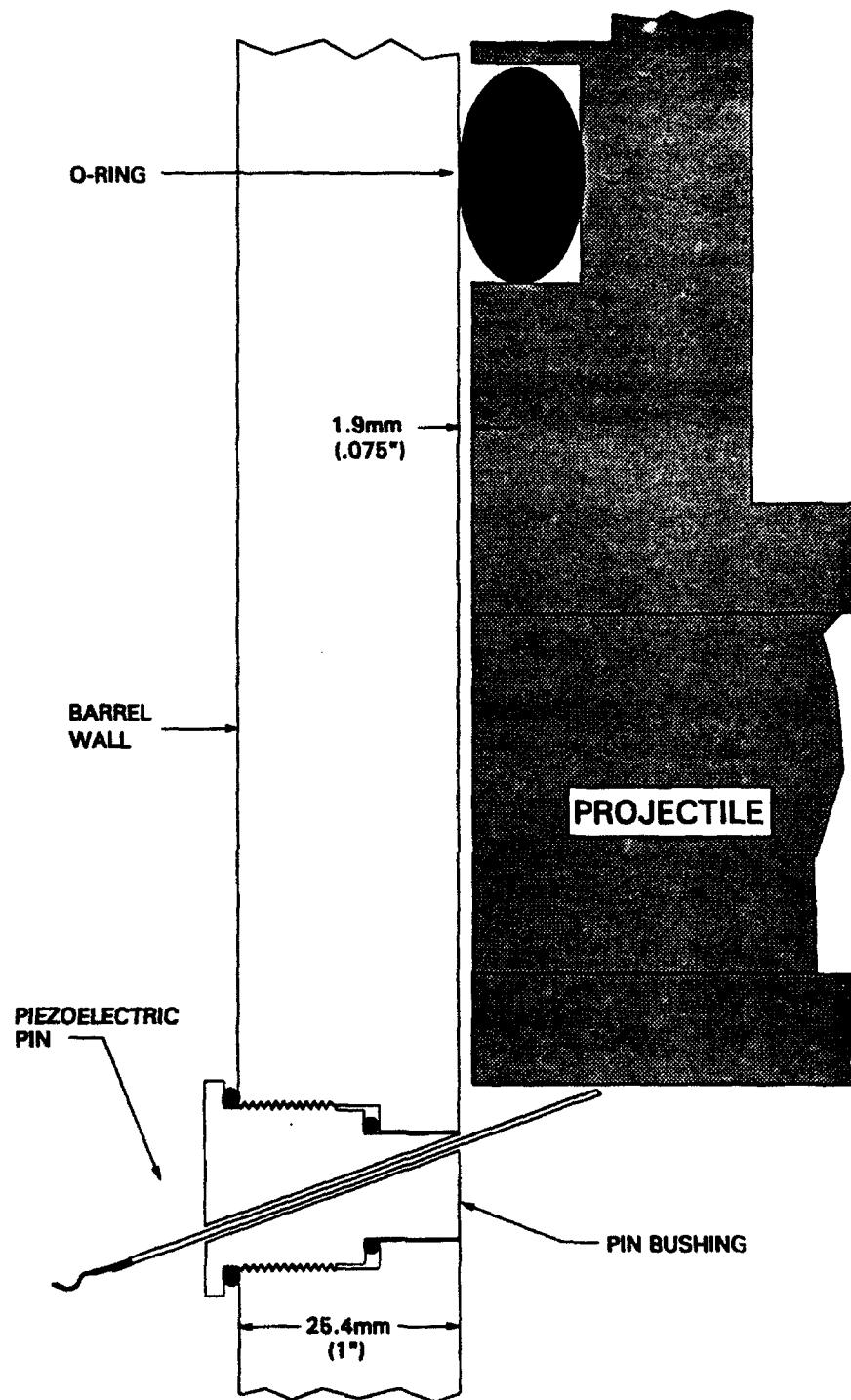
Figure 5-3. Schematic of orientation of peizoelectric pin used in measuring projectile velocity and planarity.

The FORTRAN program TOACHECK, listed in Appendix E, was used to evaluate the TOA data from each gas gun test. This program calculates the velocity and the associated accuracy for each of the two sets of pins T-1A/T-1B and T-3A/T-3B. It also calculates the maximum angle of rotation and the associated accuracy between any three of the four pin locations T-1B, T-2, T-3B, and T-4. The redundant planarity measurement is used to assess the consistency of the TOA data. A plane is fit through three of the data points and the location of the fourth point is projected. The measured value is then compared to this calculated value. This procedure is conducted for each possible combination (four total). The analysis indicated that the method used for measuring the velocity and planarity of the projectile is consistent and congruous. (Note: a detailed discussion of this analysis is beyond the scope of this report).

5.3 TEST RESULTS.

A total of 22 tests were conducted with the WES 4-ft Diameter Vertical Gas Gun (see Table 5-1 - the first two tests were preliminary exercises, and have been omitted from the table). The vessel pressure in these tests varied from 0 to 2,070 kPa (300 psi) and the projectile velocities varied from 5.4 to 71 m/sec (17.6 to 232.8 ft/sec). Multiple tests were conducted at each of several vessel pressure levels to investigate the repeatability of the gun's performance with regard to nuisance factors (ground vibration and noise) associated with testing and projectile velocity.

The measured projectile velocities for tests with the current gas gun projectile are shown in Figure 5-4. The circles in this figure represent the predicted velocity for a given vessel pressure and projectile configuration. The projectile velocity data from Table 5-1 is indicated by the small squares in the figure. The vertical bars about each velocity data point denote the accuracy of the measurements ($\pm$ 4.6 percent - discussed in Section 5.2). The use of carefully placed piezoelectric pins proved to be a reliable method of measuring the projectile velocity, with the exception of Tests 9, 16, and 17. The TOADS box was faulty on Test 9 and 16, preventing the collection of data. On Test 17, the clock speed of the TOADS box was inadvertently set

43

Table 5-1. Projectile velocity, planarity, and pressurization time from WES 4-Ft Diameter Vertical Gas Gun tests.

TEST NO.	TEST LEVEL (kPa)	PROJECTILE WEIGHT (kg)	PREDICTED PROJECTILE VELOCITY (m/sec)	MEASURED PROJECTILE VELOCITY (m/sec)	MEAS. AS PERCENT OF PREDICTION† (%)	PROJECTILE PLANARITY (milli-radians)	TIME TO PRESSURIZE (min)
3	159	761	32.3	32.0*	99	ND	6.75
4	345	761	47.9	ND	-	ND	13.5
5	0	964	8.1‡	5.4	67	2.48	0
6	345	1,452	34.1	27.9	82	.72	13.25
7	517	1,482	41.2	37.1	90	2.58	18.25
8	517	1,482	41.2	35.5	86	2.0	18.5
9	690	1,482	47.6	ND	-	ND	25.75
10	862	1,489	53.0	47.2	89	1.16	33.5
11	1,014	1,475	57.9	50.3	87	0.57	38.25
12	662	1,482	46.6	41.8	90	0.36	25.25

† (Meas. Vel.)/(Pred. Vel.) * 100

* Velocity based on one set of TOA pins

‡ Velocity calculated as $\sqrt{2gh}$

ND = No Data

44

Table 5-1. Projectile velocity, planarity, and pressurization time from WES 4-Ft
Diameter Vertical Gas Gun tests. (Continued)

TEST NO.	TEST LEVEL (kPa)	PROJECTILE WEIGHT (kg)	PREDICTED PROJECTILE VELOCITY (m/sec)	MEASURED PROJECTILE VELOCITY (m/sec)	MEAS. AS PERCENT OF PREDICTION† (%)	PROJECTILE PLANARITY (milli-radians)	TIME TO PRESSURIZE (min)
13	1,027	1,482	55.8	52.8*	95	5.2	40.25
14	1,207	1,482	60.4	55.7	92	3.64	46.25
15	1,379	1,482	64.3	59.0	92	3.2	54
16	841	1,482	50.3	ND	-	ND	32.25
17	1,165	1,482	59.1	ND	-	ND	47.45
18	1,725	1,516	71.0	64.0	90	3.47	77.75
19	1,717	1,516	71.0	63.0	89	5.16	ND
20	2,070	1,516	78.0	ND	-	ND	94
21	2,070	1,530	77.7	71.0	91	5.13	96
22	862	1,472	51.2	46.8	91	2.49	32.75
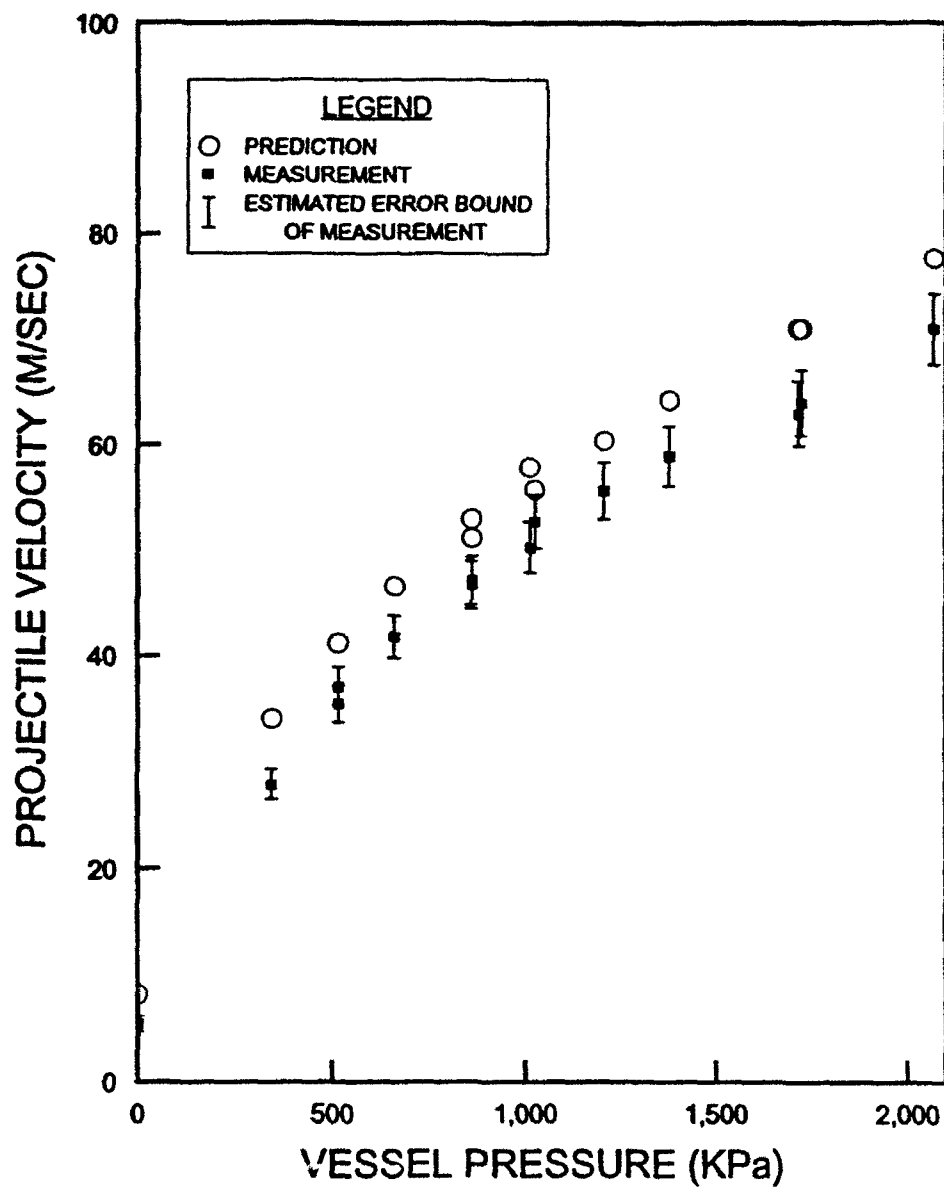
Figure 5-4. Predicted and measured projectile velocities for the WES 4-Ft Diameter Vertical Gas Gun.

to 10 kHz, rendering the data useless. Test 20 also used piezoelectric pins for measuring projectile velocity. However, larger diameter (17.5 mm) o-rings were inadvertently used on the projectile for this test. The resulting increased friction between the projectile and the barrel caused the projectile to hesitate when released by the trigger mechanism. This momentary hesitation (approximately one second) allowed the TOADS clock to expire prior to arrival of the projectile at the pin locations at the end of the barrel, thus prohibiting a measurement. Tests 3 and 4 used a side way self-shorting pin. The failure of three sets of pins out of four triggered the change in pin types to the piezoelectric pin now used.

The measured projectile velocity was, on the average, about 90 percent of the predicted value (see Table 5-1). The discrepancy between the predicted and measured values may perhaps be attributed to the friction between the projectile o-rings and the barrel (not accounted for in the mathematical model), and the weight of the water reaction mass at the top of the barrel. When the projectile was redesigned, its weight was increased from 761 kg to 1,450 kg (1,675 lb to 3,200 lb). To obtain the design maximum projectile velocity, a further increase of 818 kg (1,800 lb) in the reaction mass is required. The mass of the water has not been increased since the redesign of the projectile, since that would require increasing the height of the upper barrel section that contains the water by approximately 71 cm (28 in.).

The planarity of the projectile, as it exited the barrel, was measured on the gun performance tests. Typically, the rotation was between 2 and 5 milliradians. These results are presented in Table 5-1.

Also listed in Table 5-1 (and presented in Figure 5-5) is the time required for the air compressor to pressurize the gas gun to a given level. The air compressor currently in use can only be run intermittently at pressures greater than 1,379 kPa (200 psi), because of increased temperatures experienced by the compressor. This causes a slight increase in the amount of time required to pressurize the 4-ft gun reservoir to the higher operating pressures.
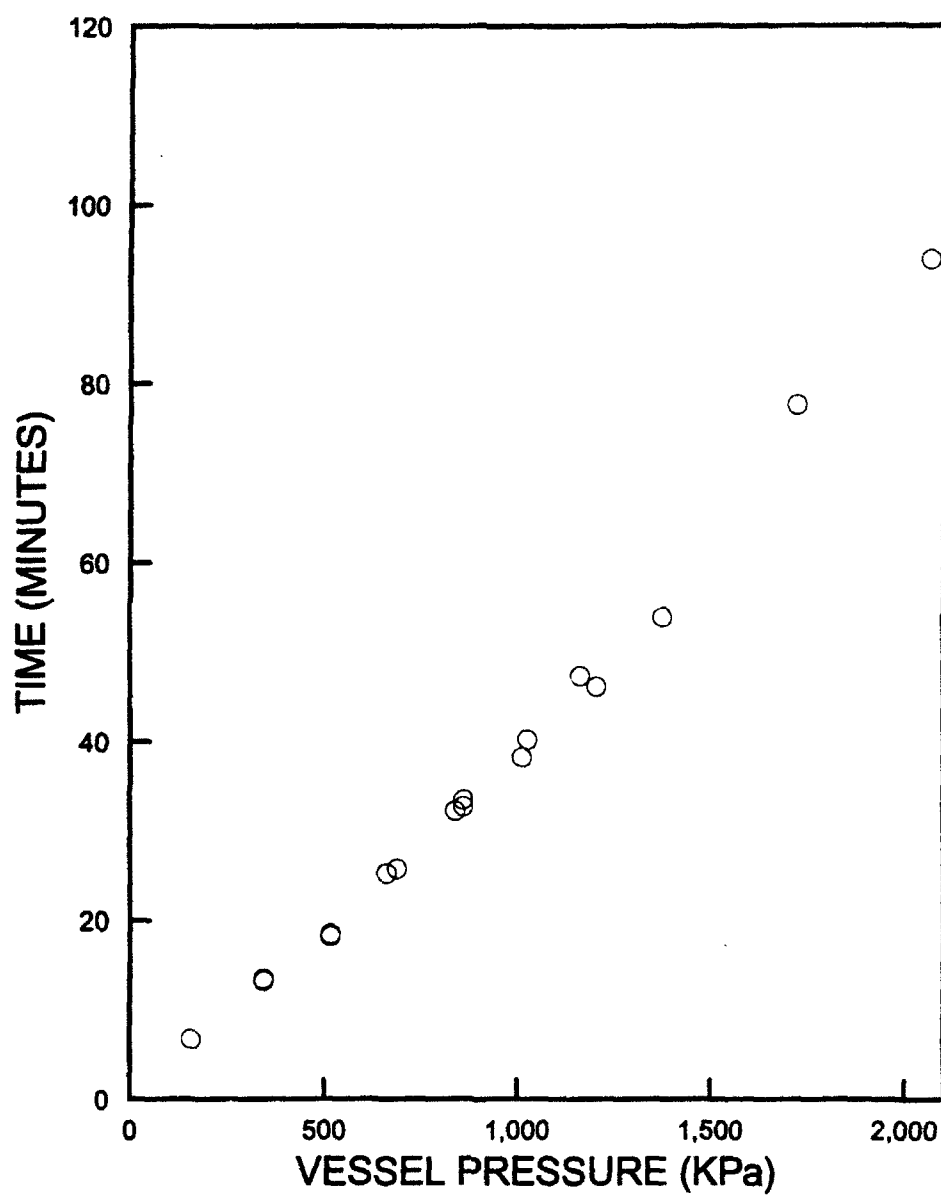
Figure 5-5. Time required to pressurize the gas gun.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS.

Twenty-two tests have been conducted with the WES 4-ft Diameter Vertical Gas Gun to date. These tests were conducted over the entire operating range of the gun (0 to 2,070 kPa (300 psi)). The projectile velocity on these tests varied from 5.4 to 71 m/sec. The projectile velocities were, on the average, about 90 percent of the values predicted by the mathematical model of the gun.

The long-range effects data collected on these tests indicates there is no potential for damage to buildings in the area from either ground shock or airblast. The noise generated from firing the gun, while relatively loud, has caused little disturbance in the surrounding area.

The redesigned projectile survived all tests and performed as expected. A carriage/impact plate configuration, of the type employed in the current design, should aid in delivering impact shock loadings with varying pulse shapes against target specimens in future tests.

The consistency and predictability of the data collected on these tests will be of significant benefit for predicting and evaluating the results of future tests with the gun.

6.2 RECOMMENDATIONS.

There should be no further requirement for the measurement of far-field ground motion and airblast on future tests. Sound pressure level measurements should be continued, as they are simple and inexpensive measurements that will document the actual long-range "nuisance" effect levels of future tests, particularly since such low-level effects are subject to variation with daily weather conditions.

Future tests will focus on the stresses and particle velocities generated in target samples of various geologic materials, which is the main purpose of the gun. Finite element/finite difference calculations, to supplement the 1-D elastic calculations (not presented in this report), should be made to aid in understanding the environments created

49

in target testbeds beneath the gun. The calculations should characterize the stress and velocity fields in a test sample. These calculations are necessary to utilize the gun as a dynamic validation facility. Calculations to vary the pulse shape input to a test article are also required to fully utilize the facility. These calculations should address axisymetrically diverging flows as well as varying pulse durations.

SECTION 7

REFERENCES

1. <u>Blaster's Handbook</u>, 16 ed., (1980). E. I. du Pont de Nemours & Co., Wilmington, Delaware.

2. Joachim, Charles E. (1985). Unpublished design calculations and sketches on the 12-in. diameter vertical gas gun. USAE Waterways Experiment Station, Vicksburg, MS 39180-6199.

3. Kinsler, Frey, Coppens, and Sanders (1982). <u>Fundamentals of Acoustics</u>, 3rd ed. Wiley, New York. 1982.

4. Langefors, U., et al, (1958). "Ground Vibrations in Blasting," Water Power. February 1958.

5. McPherson, J. A., (1989). "Blasting Vibration Damage and Noise Prediction and Control," Engineer Technical Letter 1110-1-142, U.S. Army Corps of Engineers. 1 September 1989.

6. Nicholls, H. R., et al, (1971). "Blasting Vibrations and Their Effects on Structures," Bulletin 656, U.S. Department of the Interior, Bureau of Mines. 1971.

7. Ohrt, Alan P. (1988a). Unpublished design calculations and sketches for 4-ft diameter vertical gas gun. USAE Waterways Experiment Station, Vicksburg, MS 39180-6199. November 1988 - December 1988.

8. Ohrt, Alan P. and Welch, Charles R. (1989). "Development of a 4-ft Diameter Vertical Gas Gun - Summary Program Report - FY88," letter report to the Defense Nuclear Agency. USAE Waterways Experiment Station, Vicksburg, MS 39180-6199. January 1989.

9. Ristvet, Dr. B. L., (1987). "Environmental Assessment and Finding of No Significant Impact for the Deep Underground Simulator Test Program, Continental Mine, Silver City, NM," prepared for the Director, Defense Nuclear Agency, Washington, DC. October 1987.

10. Siskind, D. E., Crum, S. V., and Plis, M. M., (1990). "Vibration Environment and Damage Characterization for Houses in McCutchanville and Daylight, Indiana," U.S. Department of the Interior, Bureau of Mines, Contract Research Report. February 1990.

11. Wallace, J. G., Fowler, J. (1973). "Fundamental Experiments in Ground Shock Phenomenology," Miscellaneous Paper N-73-2. USAE Waterways Experiment Station, Vicksburg, MS 39180-6199. March 1973.

12. White, Howard G. (1988). Unpublished design calculations and sketches for the quick-release trigger mechanism for the 12-in. diameter vertical gas gun. USAE Waterways Experiment Station, Vicksburg, MS 39180-6199.

13. White, Howard G. (1990a). Unpublished design calculations and sketches for the quick-release trigger mechanism for the 4-ft diameter vertical gas gun. USAE Waterways Experiment Station, Vicksburg, MS 39180-6199. December 1989 - January 1990.

14. White, Howard G. (1990b). Unpublished design calcualtions and sketches for the 4-ft diameter projectile. USAE Waterways Experiment Station, Vicksburg, MS 39180-6199. February 1990.

15. White, Howard G. (1990c). "Hydrostatic and Vacuum Testing of the WES 4-ft Diameter Vertical Gas Gun," letter report to the Defense Nuclear Agency. USAE Waterways Experiment Station, Vicksburg, MS 39180-6199. July 1990.

16. White, Ohrt, Welch, and Joachim (1991). "Design and Testing Experiences with the WES 12-in. and 4-ft Diameter Vertical Gas Guns," Proceedings of the Defense Nuclear Agency Instrumentation for Nuclear Weapons Effects Testing (INWET) Conference, 16-19 April 1991. Volume 1- General Session and Sessions I and II, DASIAC-TR-91-001-V1, Defense Nuclear Agency, Alexandria, VA 22310-3398. November 1991.

APPENDIX A

LIST OF ABBREVIATIONS

A area of barrel

E yield energy of TNT explosive

KE kinetic energy

F force on projectile and reaction mass

L_p distance traveled by projectile

L_r distance traveled by reaction mass

M_p projectile mass

M_r reaction mass

P peak pressure amplitude
total pressure in system

P_e effective pressure

P_{init} initial pressure acting on projectile and reaction mass

P_{ref} reference pressure

R range from source

V total system volume

V_{cham} volume of chamber between projectile and reaction mass

V_i peak vertical particle velocity for impact

V_p projectile velocity

V_{pv} volume of pressure vessel

Vel_p projectile velocity

x displacement of projectile

y displacement of reaction mass

ρ density of reaction mass

γ ratio of specific heats for a gas

APPENDIX B

STANDARD OPERATING PROCEDURE FOR THE WES 4-FT DIAMETER VERTICAL GAS GUN

STANDARD OPERATING PROCEDURE FOR THE
WES 4-FT DIAMETER VERTICAL GAS GUN

The following standard operating procedure (SOP) will be adhered to when testing with the WES 4-ft Diameter Vertical Gas Gun.

I. LOADING THE PROJECTILE:

CONTROL PANEL STATUS:

Master control switch on side of control panel "ON"

Power direct switch on side of control panel set to "GUN"

AT THE GUN:

Set regulator on nitrogen bottle to 150 psi

Hook-up battery power to fire/cock valve

Open manual valve inside barrel above trigger mechanism (always open)

Lower latches on trigger mechanism by placing fire/cock switch in "FIRE" position

Move projectile into place

Move fire/cock switch to the "COCK" position

II. PREPARING THE SITE/GUN:

Position fiberglass sheet to support water reaction mass, add foam board and plastic liner

Fill top of barrel with water

Set regulator on air tank to 50 psi

Turn on water to aftercooler

***** CLEAR ALL PERSONNEL FROM SITE *****

III. REMOTE CONTROL FOR PRESSURIZING AND BLEEDING VESSEL:

CONTROL PANEL STATUS:

Master control switch on side of control panel "ON"

Power direct switch on side of control panel set to "CONTROL PANEL"

Master control switch on front of control panel set for power to left side of control panel, left light on

All valves initially closed

PRESSURIZE SEQUENCE:

"OPEN" pressure isolation valve in pressure line

"START" air compressor

Monitor vessel pressure with the direct-reading pressure meter (units of psi) mounted in control panel

"STOP" compressor when desired pressure level is obtained

"CLOSE" pressure isolation valve in the pressure line

BLEED SEQUENCE:

"OPEN" bleed valve in pressure line

When vessel bleeding is complet , "OPEN" pressure isolation valve to bleed pressure line back to air compressor

"CLOSE" both pressure line valves

IV. REMOTE CONTROL FOR EVACUATING AND BLEEDING BARREL:

CONTROL PANEL STATUS:

Master control switch on side of control panel "ON"

Power direct switch on side of control panel set to "CONTROL PANEL"

Master control switch on front of control panel set for power to left side of control panel, left light on

All valves initially closed

EVACUATION SEQUENCE:

"OPEN" vacuum isolation valve in vacuum line

"OPEN" pressure isolation valve in vacuum line

"START" vacuum pump

Monitor vacuum in barrel with the direct-reading pressure meter (units of in. Hg) mounted in control panel

"STOP" vacuum pump when desired vacuum level is obtained

"CLOSE" vacuum isolation valve in vacuum line

"CLOSE" pressure isolation valve in vacuum line

BLEED SEQUENCE:

"OPEN" pressure isolation valve in vacuum line

"OPEN" bleed valve in vacuum line

When barrel bleeding is complete, "OPEN" vacuum isolation valve to bleed vacuum line back to vacuum pump

"CLOSE" all three vacuum line valves

V. FIRING THE GUN:

Master control switch on front of control panel set for power to right side of control panel, right light on

Sound warning horn one minute prior to firing, thirty seconds prior to firing, and three short blasts to count down final seconds prior to firing

Fire gun by moving fire/cock switch to "OPEN" position

Lower retaining collar of trigger mechanism by moving fire/cock switch to "CLOSED" position

VI. TO SHUT DOWN CONTROL PANEL:

Master control switch on front of control panel set for power to left side of control panel, left light on

Bleed the pressure and vacuum lines

"CLOSE" all valves

Move master control switch on side of control panel "OFF"

B-4

APPENDIX C

LISTING OF FORTRAN PROGRAM PARTVEL.FOR

```
C  PROGRAM NAME: PARTVEL.FOR
C  DATE: APRIL 27, 1991

C  WRITTEN BY:  HOWARD G. WHITE
C               USAE WATERWAYS EXPERIMENT STATION
C               3909 HALLS FERRY ROAD
C               VICKSBURG, MS  39180-6199
C               PH: (601) 634-3391

C  THIS PROGRAM CALCULATES THE PEAK VERTICAL PARTICLE VELOCITY
C  FOR IMPACTS AS A FUNCTION OF RANGE AND PROJECTILE SEISMIC ENERGY
C  LEVEL ASSUMING A TNT EQUIVALENCE OF 1.41E6 FT-LB/LB-TNT.  THE
C  PROJECTILE'S KINETIC ENERGY IS FOUND FROM ITS MASS AND VELOCITY.

C  REFERENCE:  FUNDAMENTAL EXPERIMENTS IN GROUND SHOCK PHENOMENOLOGY
C              WES MISCELLANEOUS PAPER N-73-2
C              J.G. WALLACE AND J. FOWLER
C              MARCH 1973
C              PARAGRAPH 28, P36.

C  VARIABLE DEFINITION

C  GC - GRAVITATIONAL CONSTANT (LBm-FT/LBf-SEC^2)
C  E - ENERGY OF IMPACT (LB-TNT)
C  MP - MASS OF PROJECTILE (LBm)
C  PARTVEL - PARTICLE VELOCITY AT RANGE R (IN/SEC)
C  PROJVEL - PROJECTILE VELOCITY (FT/SEC)
C  R - RANGE (FT)
C  TNT - TNT EQUIVALENCE
C  VMIN - MINIMUM VELOCITY USED IN CALCULATION (FT/SEC)
C  VMAX - MAXIMUM VELOCITY USED IN CALCULATION (FT/SEC)

C  ****************************************************************
       INTEGER VMIN,VMAX
       REAL MP
       CHARACTER OUTFILE*15

10     CONTINUE

C  **** DEFINE CONSTANTS ****

       GC=32.174
       TNT=1410000.0
       MP=3260.
       VMIN=1
       VMAX=300

       WRITE(*,50)GC,TNT,MP,VMIN,VMAX
50     FORMAT(//,5X,'CURRENT PARAMETER SETTINGS ARE : ',
      1//,5X,'GRAVITATIONAL CONSTANT - ',F6.3,' (LBm-FT)/(LBf-SEC^2)',
      2//,5X,'TNT EQUIVALENCE - ',F8.0,' (FT-LBf)/(LBf-TNT)',
      3//,5X,'PROJECTILE MASS - ',F5.0,' LBm',
```

```fortran
     4//,5X,'RANGE OF PROJECTILE VELOCITY CALCULATED : ',I2,' TO ',
     5   I3,' FT/SEC',//)

       WRITE(*,60)
60     FORMAT(5X,'UNITS OF THE RESULTING PARTICLE VELOCITY ARE IN/SEC')

       WRITE(*,70)
70     FORMAT(//,5X,'INPUT THE RANGE OF THE OBSERVATION POINT (FT) : ')
       READ(*,*)R

       WRITE(*,80)
80     FORMAT(//,5X,'OUTPUT FILE NAME : ')
       READ(*,90)OUTFILE
90     FORMAT(A15)
       OPEN(UNIT=17,FILE=OUTFILE)
       WRITE(17,*)VMAX

C  **** CALCULATION SECTION ****

       DO 100 I=VMIN,VMAX
         PROJVEL=I*1.0

C  **** EQN (4) IN NOTES ****
         E=MP*PROJVEL*PROJVEL/(2.0*GC*1410000.)

C  **** EQN (17) IN REFERENCE WITH UNITS OF IN/SEC ****
         PARTVEL=600.0*(E/R**3)**0.5

         WRITE(17,*)PROJVEL,PARTVEL

100    CONTINUE

       CLOSE (UNIT=17)

350    WRITE(*,*)'      DO YOU WISH TO RUN THIS PROGRAM AGAIN?'
       WRITE(*,*)'      YES = 1      NO = 2'
       WRITE(*,*)'      PREFERENCE: '
       READ(*,*)IPREF
       IF(IPREF.EQ.1) GOTO 10

1000   END
```

APPENDIX D

LISTING OF FORTRAN PROGRAM GG4PV.FOR

```
C  PROGRAM NAME: GG4PV.FOR
C  UPDATED: OCTOBER 30, 1992
C  DATE: JULY 10, 1991

C  UPDATE NOTES:  NOW ALLOW OPTIONS OF USING A PRESSURE PLATE ON
C  THE PROJECTILE AND TO REDUCE XL BY THE ADDITION OF FOAM AND AN IMPACT
C  PLATE TO THE FRONT OF THE PROJECTILE.

C  WRITTEN BY:  HOWARD G. WHITE
C               USAE WATERWAYS EXPERIMENT STATION
C               3909 HALLS FERRY ROAD
C               VICKSBURG, MS  39180-6199
C               PH: (601) 634-3391

C  THIS PROGRAM CALCULATES THE PROJECTILE VELOCITY FOR THE 4-FT
C  GAS GUN, FOR A GIVEN VESSEL PRESSURE, OR RANGE OF PRESSURES,
C  AND A GIVEN PROJECTILE WEIGHT.

C  REFERENCE:  AL OHRT'S AND MY NOTES ON "THEORETICAL ANALYSIS OF
C              PRESSURE-VELOCITY CURVES" IN THE "4-FT GAS GUN
C              CALCULATIONS" NOTEBOOK

C              "DESIGN AND TESTING EXPERIENCES WITH THE WES 12-IN.
C              AND 4-FT DIAMETER VERTICAL GAS GUN".  WHITE, OHRT, WELCH
C              AND JOACHIM.  1991 DNA INWET CONFERENCE

C  VARIABLE DEFINITION
C  C - CONVENIENT CONSTANT
C  COEFF1 - CONVENIENT CONSTANT
C  COEFF2 - CONVENIENT CONSTANT
C  COEFF3 - CONVENIENT CONSTANT
C  DENRM - DENSITY OF REACTION MASS (SLUGS/FT^3)
C  I - DUMMY VARIABLE
C  ICALC - 1 IF CALC VEL AS FRONT EXITS BARREL, 2 IF REAR
C  IPPLATE - 2 IF PRESSURE PLATE IS USED ON PROJECTILE, 1 IF NOT
C  OUTFILE - OUTPUT FILENAME FOR CALCULATED DATA
C  PINC - PRESSURE INCREMENT FOR CALCULATIONS (PSI, CHANGED TO LB/FT^2)
C  PINIT - INITIAL VESSEL PRESSURE (PSI)
C  PMASSLB - PROJECTILE MASS (LBm, CHANGED TO SLUGS)
C  PMASS - PROJECTILE MASS (SLUGS)
C  PMAX - MAX PRESSURE FOR CALCULATIONS (PSI)
C  RATIO - RATIO OF PROJECTILE MASS TO REACTION MASS
C  RBAR - RADIUS OF BARREL (FT)
C  RMASS - REACTION MASS (SLUGS)
C  VCHAM - VOL OF CHAMBER BETWEEN PROJECTILE AND REACTION MASS (FT^3)
C  VEL - VELOCITY OF PROJECTILE (FT/SEC)
C  VINIT - INITIAL PRESSURIZED VOL, BEFORE MASSES BEGIN MOVING (FT^3)
C  VTANK - VOLUME OF TANK (FT^3)
C  XFOAM - LENGTH OF FOAM ADDED TO FRONT OF PROJECTILE (IN CHANGED TO FT)
C  XL - LENGTH OF PROJECTILE TRAVEL PRIOR TO IMPACTING RATE PINS (FT)
C  XPLATE - LENGTH OF IMPACT PLATE (IN CHANGED TO FT)
C  YL - LENTH OF REACTION MASS HEIGHT (AND TRAVEL) (FT)
```

```
C  ****************************************************************
      CHARACTER OUTFILE*15

C **** INPUT PROJECTILE MASS ****

10    WRITE(*,90)
90    FORMAT(///,5X,'PROGRAM GG4PV (LAST UPDATED: 30 OCTOBER 1992)')

      WRITE(*,100)
100   FORMAT(///,5X,'INPUT PROJECTILE MASS (LBm) : ')
      READ(*,*)PMASSLB

      WRITE(*,110)
110   FORMAT(///,5X,'INPUT LENGTH OF FOAM ON PROJECTILE (IN) : ')
      READ(*,*)XFOAM

      WRITE(*,120)
120   FORMAT(///,5X,'INPUT LENGTH OF IMPACT PLATE (IN) : ')
      READ(*,*)XPLATE

125   WRITE(*,130)
130   FORMAT(///,5X,'WAS A PRESSURE PLATE USED ON THE PROJECTILE?',
     1       /,5X,'1 - NO          2 - YES',
     2       //,5X,'ENTER OPTION : ')
      READ(*,*)IPPLATE
      IF(IPPLATE.LT.1 .OR. IPPLATE.GT.2) THEN
        WRITE(6,*)'YOU ENTERED : ',IPPLATE
        WRITE(6,*)'PLEASE ENTER A 1 OR 2'
        GOTO 125
      END IF

135   WRITE(*,140)
140   FORMAT(///,5X,'CALCULATE THE VELOCITY AS:',
     1       /,5X,'1 - THE FRONT OF THE PROJECTILE EXITS THE BARREL',
     2       /,5X,'2 - THE REAR OF THE PROJECTILE EXITS THE BARREL',
     3       //,5X,'ENTER OPTION : ')
      READ(*,*)ICALC
      IF(ICALC.LT.1 .OR. ICALC.GT.2) THEN
        WRITE(6,*)'YOU ENTERED : ',ICALC
        WRITE(6,*)'PLEASE ENTER A 1 OR 2'
        GOTO 135
      END IF

C  **** INITIAL CONSTANTS AND CALCULATIONS ****

      PI = 3.141592654
      RBAR = 2.0
      DENRM = 1.939
      XFOAM=XFOAM/12.
      XPLATE=XPLATE/12.
      IF (ICALC .EQ. 1) THEN
        XL = (128.375-XFOAM-XPLATE)/12.
```

```
      ELSE
        XL - 166./12.
      END IF
      PMASS - PMASSLB/32.174
      VTANK - 355.0
      IF (IPPLATE .EQ. 1) THEN
        VCHAM - 63.7
      ELSE
        VCHAM - 33.0
      END IF
      VINIT - VTANK+VCHAM

C  **** CALCULATE REACTION MASS TRAVEL DISTANCE AND MASS ****

      ZZ - XL*PMASS
      Z - PI*RBAR*RBAR*DENRM
C  **** SEE OHRT'S NOTES, P9, EQN 21, OR MY NOTES, P17, EQN 21 ****
      YL - SQRT(ZZ/Z)
      RMASS - YL*Z

C  **** CALCULATE CONVENIENT CONSTANTS ****
C  **** SEE MY NOTES, P16, EQN 12 ****
      RATIO - PMASS/RMASS
      C - PI*RBAR*RBAR*(1.+RATIO)
      COEFF1 - (1.-(VINIT/(VINIT+XL*C))**0.4)
      COEFF3 - ((VTANK/VINIT)**1.4)/0.4*2.
C  **** SEE INWET PAPER, P8, EQN 5 ****
      COEFF2 - (COEFF3*VINIT)/(PMASS*(1.+RATIO))

C  **** CALCULATE ONE OR MANY POINTS? ****

150   WRITE(*,160)
160   FORMAT(///,5X,'                    OPTIONS',
     1        //,5X,'1 - GENERATE DATA FILE FOR RANGE OF PRESSURES',
     2        /,5X,'2 - INVESTIGATE SINGLE PRESSURE',
     3        //,5X,'ENTER OPTION : ')
      READ(*,*)IOPT
      IF(IOPT.LT.1 .OR. IOPT.GT.2) THEN
        WRITE(6,*)'YOU ENTERED : ',IOPT
        WRITE(6,*)'PLEASE ENTER A 1 OR 2'
        GOTO 150
      END IF

      IF(IOPT.EQ.2) GOTO 300

C  **** SECTION TO CALCULATE FOR A RANGE OF PRESSURES ****

200   WRITE(*,210)
210   FORMAT(///,5X,'INPUT MAXIMUM PRESSURE OF INTEREST (PSI) : ')
      READ(*,*)PMAX

      WRITE(*,220)
```

D-4

```fortran
220     FORMAT(/,5X,'INPUT INCREMENT FOR PRESSURE STEPS (PSI) : ')
        READ(*,*)PINC

        WRITE(*,230)
230     FORMAT(/,5X,'ENTER THE NAME OF THE OUTPUT FILE : ')
        READ(*,240)OUTFILE
240     FORMAT(A15)

        NPTS = INT(PMAX/PINC)+1
        PINC = PINC*144.

        OPEN(UNIT=10,FILE=OUTFILE)
        WRITE(10,250)NPTS
250     FORMAT(I5)

C ****  BEGIN LOOP CALCULATIONS  ****

        DO 260 I=1,NPTS
           PRES = (I-1)*PINC
C ****  SEE MY NOTES, P16, EQN 12 ****
C ****  SEE INWET PAPER, P8, EQN 9 ****
           VEL = (PRES*COEFF1*COEFF2)**0.5
           PRES = PRES/144.
           WRITE(10,*)PRES,VEL
260     CONTINUE
        CLOSE(UNIT=10)
        GOTO 400

C ****  SECTION TO CALCULATE VELOCITY FOR A SINGLE POINT ****
300     WRITE(*,310)
310     FORMAT(///,5X,'INPUT INITIAL VESSEL PRESSURE (PSI) : ')
        READ(*,*)PINIT
C ****  SEE MY NOTES, P16, EQN 12 ****
        VEL = (PINIT*144.*COEFF1*COEFF2)**0.5
        YL = YL*12.
        RMASS = RMASS*32.174
        WRITE(*,320)PINIT,VEL,YL,RMASS,PMASSLB
320     FORMAT(/,5X,'INITIAL PRESSURE = ',F4.0,' PSI',
     1          /,5X,'PROJECTILE VELOCITY = ',F4.0,' FT/SEC',
     2          /,5X,'REACTION MASS HEIGHT = ',F5.1,' INCHES',
     3          /,5X,'REACTION-MASS MASS = ',F5.0,' LBm',
     4          /,5X,'PROJECTILE MASS = ',F5.0,' LBm')

C ****  END CALCULATIONS ****

C ****  RUN THE PROGRAM AGAIN? ****

400     WRITE(*,410)
410     FORMAT(//,5X,'        OPTIONS',
     1          //,5X,'1 = RUN PROGRAM AGAIN',
     2           /,5X,'2 = END PROGRAM',
     3          //,5X,'ENTER OPTION : ')
```

```
      READ(*,*)IOPT
      IF(IOPT.LT.1 .OR. IOPT.GT.2) THEN
        WRITE(6,*)'YOU ENTERED : ',IOPT
        WRITE(6,*)'PLEASE ENTER A 1 OR 2'
        GOTO 400
      END IF
      IF (IOPT.EQ.1) GOTO 10

1000  END
```

APPENDIX E

LISTING OF FORTRAN PROGRAM TOACHECK.FOR

```
C  PROGRAM NAME: TOACHECK.FOR
C  DATE: NOV 25, 1991

C  WRITTEN BY:  HOWARD G. WHITE
C               USAE WATERWAYS EXPERIMENT STATION
C               STRUCTURES LABORATORY/EXPLOSION EFFECTS DIVISION
C               ATTN: CEWES-SE-R
C               3909 HALLS FERRY ROAD
C               VICKSBURG, MS  39180-6199
C               (601) 634-3391

C  REFERENCE:   GAS GUN TESTING NOTEBOOK
C               PERFORMANCE TEST NO. 5
C               NOTES ON ANALYSIS OF VELOCITY AND PLANARITY MEASUREMENT

C  GIVEN THE SIX TIME OF ARRIVAL (TOA) MEASUREMENTS RECORDED AT THE BASE
C  OF THE BARREL OF THE WES FOUR FT DIAMETER VERTICAL GAS GUN, THIS
C  PROGRAM CALCULATES THE VELOCITY AT TWO LOCATIONS AND THE AVERAGE
C  VELOCITY OF THE TWO.  THE RELATIVE DISTANCE BETWEEN THE FOUR LOCATIONS
C  ON THE BOTTOM PLATE OF THE PROJECTILE (USED AS A PLANARITY CHECK) ARE
C  THEN CALCULATED BY FINDING THE FIRST TOA AND SUBTRACTING IT FROM THE
C  THREE OTHER TOA MEASUREMENTS.  THIS TIME INCREMENT IS THEN MULTIPLIED
C  BY THE AVERAGE VELOCITY TO DETERMINE THE RELATIVE DISTANCE BETWEEN THE
C  FOUR POINTS.  THE XYZ COORDINATES ARE THEN KNOWN FOR EACH LOCATION.
C  THREE OF THESE POINTS ARE THEN USED TO DETERMINE THE EQUATION OF THE
C  PLANE THAT PASSES THRU THEM.  THIS EQUATION IS THEN USED TO CALCULATE
C  THE Z-COORDINATE OF THE FOURTH POINT.  THE PERCENT DIFFERENCE BETWEEN
C  THE CALCULATED VALUE AND THE EXPERIMENTAL VALUE (INCLUDING PLACEMENT
C  TOLERANCES) IS THEN DETERMINED.  THIS "CHECK" IS MADE FOR ALL FOUR
C  POINTS BY USING THE EQUATION OF THE PLANE THROUGH THE OTHER THREE PTS.

C  VARIABLES USED IN THIS PROGRAM INCLUDE

C  COEFF1 - COEFFICIENT OF X IN EQN OF A PLANE
C  COEFF2 - COEFFICIENT OF Y IN EQN OF A PLANE
C  COEFF3 - COEFFICIENT OF Z IN EQN OF A PLANE
C  CONST - CONSTANT TERM IN EQN OF PLANE
C  D - DISTANCE BETWEEN PIN LOCATIONS FOR VELOCITY MEASUREMENT (METERS)
C  DIA - DIAMETER BETWEEN TIPS OF TOA PINS (METERS)
C  DTMAX - MAX DIFFERENCE IN TOA MEASUREMENTS (SEC)
C  DT(*) - DIFF IN TOA BETWEEN A PIN LOCATION AND TOAMIN (SEC)
C  DT*U - DIFF IN TOA BETWEEN A PIN LOCATION AND TOAMIN (MICROSECONDS)
C  IANS - ORIENTATION OF PINS, 1-20 DEG, 2-HORIZONTAL
C  IVEL - AVERAGE VELOCITY EQUALS EITHER VEL1 OR VEL3
C  PINMAX - PIN LOCATION OF MAX ANGLE OF IMPACT, RELATIVE TO PINMIN
C  PINMIN - PIN LOCATION OF TOAMIN
C  R*-RADIAL DISTANCE BETWEEN LOCATION OF TOAMIN AND LOCATION * (METERS)
C  RAD - RADIUS BETWEEN TIPS OF TOA PINS (METERS)
C  SM - LOCATION OF THE SCRIBE MARK FROM THE TIP OF THE TOA PIN (IN)
C  T1A - TOA AT PIN T-1A (SEC)
C  T3A - TOA AT PIN T-3A (SEC)
C  THETA*-ANGLE OF IMPACT BETWEEN LOCATION OF TOAMIN AND LOCATION *(RAD)
```

```
C    THETAMAX - MAX ANGLE OF IMPACT (MILLIRADIANS)
C    THETATOL-TOL ON ANG OF IMPACT ASSOC W/ MAX ANG OF IMPACT(MILLIRADIANS)
C    TOA(*) - TOAs AT THE FOUR PLANARITY CHECKPOINTS (SEC)
C    TOAMAX - MAXIMUM TOA VALUE (SEC)
C    TOAMIN - MINIMUM TOA VALUE (SEC)
C    TOL - ABSOLUTE TOLERANCE ON PLACEMENT OF PINS, (METERS)
C    TOLMM - TOLERANCE ON PLACEMENT OF PINS, BEST WE CAN DO (MILLIMETERS)
C    TOLPM-PLUS OR MINUS TOLER.NCE ON PLACEMENT OF PINS, 1/2 OF TOL(METERS)
C    TOLPMMM-PLUS OR MINUS TOLERANCE ON PLACEMENT OF PINS, 1/2 OF TOL (MM)
C    VEL1 - VELOCITY AT PIN LOCATION 1 (M/SEC)
C    VEL3 - VELOCITY AT PIN LOCATION 3 (M/SEC)
C    VELLB-MINIMUM VELOCITY PLUS ITS ASSOCIATED VELOCITY TOLERANCE (M/SEC)
C    VELTOL* - TOLERANCE ON VELOCITY AT PIN LOCATION * (M/SEC)
C    VELUB-MAXIMUM VELOCITY MINUS ITS ASSOCIATED VELOCITY TOLERANCE (M/SEC)
C    VELAVG - AVERAGE VELOCITY (M/SEC)
C    VELAVGFPS - AVERAGE VELOCITY (F/SEC)
C    X* - X COORDINATE OF PLANARITY CHECK PINS (METERS)
C    X*MM - X COORDINATE OF PLANARITY CHECK PINS (MILLIMETERS)
C    Y* - Y COORDINATE OF PLANARITY CHECK PINS (METERS)
C    Y*MM - Y COORDINATE OF PLANARITY CHECK PINS (MILLIMETERS)
C    Z* - Z COORDINATE OF PLANARITY CHECK PINS (METERS)
C    Z*C - CALC VALUE OF Z* BASED ON EQN OF PLANE THRU OTHER PINS (METERS)
C    Z*CMM - CALC VALUE OF Z* BASED ON EQN OF PLANE THRU OTHER PINS (MM)
C    Z*MAX - MAX VALUE BETWEEN Z* AND Z*C (METERS)
C    Z*MIN - MIN VALUE BETWEEN Z* AND Z*C (METERS)
C    Z*MM - Z COORDINATE OF PLANARITY CHECK PINS (MILLIMETERS)
C    ZDIF*MAX - MAX % DIFF BETWEEN CALC AND ACTUAL VALUE OF PIN LOCATIONS
C    ZDIF*MIN - MIN % DIFF BETWEEN CALC AND ACTUAL VALUE OF PIN LOCATIONS
C    ZTOL* - % DIFF BETWEEN TOLERANCE ON PLACEMENT & ACTUAL PIN LOCATION


C    ***************************************************************

     DIMENSION TOA(4),DT(4)
   . DOUBLE PRECISION TOA,DT,TOAMIN
     CHARACTER PINMIN*4,PINMAX*4
     IVEL - 0

C CONVERT 20 DEGREE PIN PLACEMENT ANGLE FROM DEGREES TO RADIANS
     PI-3.141592654
     ANGLE-20./180.*PI

     WRITE (*,5)
5    FORMAT(//////,5X,'PROGRAM: TOACHECK',//,5X,'TEST NAME:   ')
     READ (*,*)
     WRITE (*,10)
10   FORMAT(//,5X,'INPUT THE TOA DATA FOR THE SIX PINS',
    2       ///,15X,'PIN NUMBER T-1A (SEC): ')
     READ(*,*)T1A
     WRITE (*,20)
20   FORMAT(//,15X,'PIN NUMBER T-1B (SEC): ')
     READ (*,*)TOA(1)
     WRITE (*,30)
```

E-3

```fortran
30      FORMAT(//,15X,'PIN NUMBER T-2 (SEC): ')
        READ (*,*)TOA(2)
        WRITE (*,40)
40      FORMAT(//,15X,'PIN NUMBER T-3A (SEC): ')
        READ (*,*)T3A
        WRITE (*,50)
50      FORMAT(//,15X,'PIN NUMBER T-3B (SEC): ')
        READ (*,*)TOA(3)
        WRITE (*,60)
60      FORMAT(//,15X,'PIN NUMBER T-4 (SEC): ')
        READ (*,*)TOA(4)
64      WRITE(*,65)
65      FORMAT(///,5X,'WERE THE TOA PINS PLACED',
        1       ' AT A 20 DEGREE ANGLE (1) OR HORIZONTALLY (2) ?',
        2       /,15X,'ORIENTATION: ')
        READ(*,*)IANS
        IF (IANS.EQ.1 .OR. IANS.EQ.2) THEN
          GOTO 67
        ELSE
          WRITE (*,66)
66        FORMAT(/,15X,'INPUT A 1 OR 2 PLEASE!')
          GOTO 64
        ENDIF
67      WRITE (*,68)
68      FORMAT(///,5X,'INPUT THE LOCATION OF THE SCRIBE',
        1       /,5X,'MARK FROM THE TIP OF THE TOA PIN (IN): ')
        READ(*,*)SM


C AN ASSUMPTION HERE IS THAT THE X AND Y LOCATIONS OF THE PINS DOES
C NOT CHANGE, IE, THE CENTER OF THE PROJECTILE IS IN THE CENTER OF THE
C BARREL AT THE TIME OF PIN IMPACT.

C TOLERANCES ON THE VELOCITY AND PLANARITY MEASUREMENTS
C     FACTOR                            TOLERANCE (+ OR -)
C                                20 DEGREE ANGLE         HORIZONTAL
C PIN PLACEMENT                     0.005"               0.000"
C RECEPTACLE LOCATION               0.001"               0.001"
C PIN HOLES IN RECEPTACLE           0.002"               0.000"
C FLATNESS OF IMPACT PLATE          0.005"               0.005"
C PROJECTILE ASSEMBLY               0.010"               0.010"
C TOTAL                  + OR - 0.023"         + OR - 0.016"
C ABSOLUTE TOLERANCE                0.046"               0.032"

C DIA IS DIAMETER BETWEEN PINS RESULTING FROM A PLACEMENT MARK AT SM".
C THE ANGLE AT WHICH THE PIN IS PLACED IS 20 DEGREES.

        IF(IANS.EQ.2) THEN
          TOL=0.032
          DIA=48. - (2.*SM)
        ELSE
          TOL=0.046
          DIA=48. - (2.*(SM*COS(ANGLE)))
```

```
      ENDIF

C  CONVERT TOLERANCE TO MILLIMETERS AND METERS AND DIAMETER TO METERS
      TOLMM=TOL*25.4
      TOL=TOL*0.0254
      TOLPM=TOL/2.
      TOLPMMM=TOLMM/2.
      DIA=DIA/12./3.28
      RAD=DIA/2.


C  CALC THE VELOCITY AT LOCATIONS 1 AND 3
C  THE DISTANCE BETWEEN THE PINS IS 1", CHANGED TO METERS

      D = 1./12./3.28
      VEL1 = D/(TOA(1)-T1A)
      VELTOL1 = TOL/(TOA(1)-T1A)
      VEL3 = D/(TOA(3)-T3A)
      VELTOL3 = TOL/(TOA(3)-T3A)
      WRITE (*,70) VEL1,VELTOL1,VEL3,VELTOL3
70    FORMAT(///,5X,'THE VELOCITY AT PIN LOCATION 1 IS: ',F6.2,' M/SEC',
     1        /,5X,'                      PLUS OR MINUS: ',F6.3,' M/SEC',
     2       //,5X,'THE VELOCITY AT PIN LOCATION 3 IS: ',F6.2,' M/SEC',
     3        /,5X,'                      PLUS OR MINUS: ',F6.3,' M/SEC')

C  CHECK TO SEE IF THE AVG VELOCITY WITHIN THE BOUNDS OF THE TOLERANCES

      VELAVG = (VEL1+VEL3)/2.
      VELMIN=AMIN1(VEL1,VEL3)
      VELMAX=AMAX1(VEL1,VEL3)
      IF (VELMIN.EQ.VEL1) THEN
         VELLB=VELMIN+VELTOL1
         VELUB=VELMAX-VELTOL3
      ELSE
         VELLB=VELMIN+VELTOL3
         VELUB=VELMAX-VELTOL1
      ENDIF

         VELAVGFPS = VELAVG*3.28

      IF(VELAVG.LT.VELLB .OR. VELAVG.GT.VELUB) THEN
         WRITE(*,72)VELAVG,VELAVGFPS,VELUB,VELLB
72       FORMAT(//,5X,'THE AVERAGE VELOCITY:        ',F6.2,' M/SEC',
     1'        ',F5.1,' FPS',/,5X,'IS WITHIN THE UPPER BOUND: ',F6.2,
     2' M/SEC',/,5X,'AND THE LOWER BOUND:        ',F6.2,' M/SEC',
     3        /,5X,'OF THE VELOCITY MEASUREMENTS.'
     4    /,5X,'NOTE:  THE UPPER BOUND IS THE MAXIMUM VELOCITY MINUS',
     5    /,5X,'          ITS ASSOCIATED TOLERANCE.'
     6    /,5X,'NOTE:  THE LOWER BOUND IS THE MINIMUM VELOCITY PLUS',
     7    /,5X,'          ITS ASSOCIATED TOLERANCE.')
      ELSE
         WRITE(*,74)VELAVG,VELAVGFPS,VELUB,VELLB
74       FORMAT(//,5X,'THE AVERAGE VELOCITY:          ',F6.2,' M/SEC',
```

```fortran
      1'       ',F5.1,' FPS',/,5X,'IS NOT WITHIN THE UPPER BOUND: ',F6.2,
      2' M/SEC',/,5X,'AND THE LOWER BOUND:           ',F6.2,' M/SEC',
      3            /,5X,'OF THE VELOCITY MEASUREMENTS.'
      4   /,5X,'NOTE:  THE UPPER BOUND IS THE MAXIMUM VELOCITY MINUS',
      5   /,5X,'          ITS ASSOCIATED TOLERANCE.'
      6   /,5X,'NOTE:  THE LOWER BOUND IS THE MINIMUM VELOCITY PLUS',
      7   /,5X,'          ITS ASSOCIATED TOLERANCE.')

75       WRITE(*,76)VEL1,VEL3
76       FORMAT(//,5X,'CONTINUE THE PROGRAM WITH EITHER:',//,15X,
      1'VEL1 = ',F6.2,/,8X,'OR',5X,'VEL3 = ',F6.2,//,5X,'AS THE AVERAGE',
      2' VELOCITY.',//,5X,'ENTER A "1" OR A "3": ')
         READ(*,*)IVEL
           IF(IVEL.EQ.1 .OR. IVEL.EQ.3) THEN
             GOTO 79
    -    ELSE
             WRITE(*,78)
78           FORMAT(//,5X,'INPUT A 1 OR 3 PLEASE!')
             GOTO 75
           ENDIF
79    ENDIF


      IF(IVEL.EQ.1) THEN
         VELAVG = VEL1
      ELSEIF(IVEL.EQ.3)THEN
         VELAVG = VEL3
      ENDIF


      WRITE(*,80)
80    FORMAT(//,5X,'PRESS ANY KEY TO CONTINUE',//)
      READ(*,*)


C  CALCULATE THE DIFFERENCE IN TOA (DT(*)) AND DEFINE Z* BASED ON VELAVG
C  ZTOL* IS MADE A LARGE NUMBER WHEN THE PERCENT DIFFERENCE IS CHECKED
C  AGAINST THE LOCATION WHERE TOAMIN HAS BEEN DETERMINED.  THIS LOCATION
C  HAS A Z VALUE EQUAL TO ZERO.  THE PERCENT DIFFERENCE CANNOT BE
C  DETERMINED WHEN COMPARING A CALCULATION TO ZERO.
C  THE LARGE NUMBER WILL PRINT TO THE SCREEN AS ******

C  FIND THE MINIMUM AND MAXIMUM TOA VALUE
      TOAMIN = TOA(1)
      DO 90 I=2,4
         TOAMIN = DMIN1(TOAMIN,TOA(I))
90    CONTINUE

      IF (TOAMIN.EQ.TOA(1)) THEN
        PINMIN='T-1B'
        DT(1)=0.
        DT(2)=TOA(2)-TOA(1)
        DT(3)=TOA(3)-TOA(1)
        DT(4)=TOA(4)-TOA(1)
        X1=0.
```

```
      Y1-0.
      Z1-0.
      X2--RAD
      Y2-RAD
      Z2-VELAVG*DT(2)
      X3-0.
      Y3-DIA
      Z3-VELAVG*DT(3)
      X4-RAD
      Y4-RAD
      Z4-VELAVG*DT(4)
    ELSE IF (TOAMIN.EQ.TOA(2)) THEN
      PINMIN-'T-2'
      DT(1)-TOA(1)-TOA(2)
      DT(2)-0.
      DT(3)-TOA(3)-TOA(2)
      DT(4)-TOA(4)-TOA(2)
      X1-RAD
      Y1-RAD
      Z1-VELAVG*DT(1)
      X2-0.
      Y2-0.
      Z2-0.
      X3--RAD
      Y3-RAD
      Z3-VELAVG*DT(3)
      X4-0.
      Y4-DIA
      Z4-VELAVG*DT(4)
    ELSE IF (TOAMIN.EQ.TOA(3)) THEN
      PINMIN-'T-3B'
      DT(1)-TOA(1)-TOA(3)
      DT(2)-TOA(2)-TOA(3)
      DT(3)-0.
      DT(4)-TOA(4)-TOA(3)
      X1-0.
      Y1-DIA
      Z1-VELAVG*DT(1)
      X2-RAD
      Y2-RAD
      Z2-VELAVG*DT(2)
      X3-0.
      Y3-0.
      Z3-0.
      X4--RAD
      Y4-RAD
      Z4-VELAVG*DT(4)
    ELSE
      PINMIN-'T-4'
      DT(1)-TOA(1)-TOA(4)
      DT(2)-TOA(2)-TOA(4)
      DT(3)-TOA(3)-TOA(4)
```

```fortran
      DT(4)=0.
      X1=-RAD
      Y1=RAD
      Z1=VELAVG*DT(1)
      X2=0.
      Y2=DIA
      Z2=VELAVG*DT(2)
      X3=RAD
      Y3=RAD
      Z3=VELAVG*DT(3)
      X4=0.
      Y4=0.
      Z4=0.
      ENDIF

C  CONVERT DT(*) TO MICROSECONDS TO PRINT TO SCREEN
      DT1U = DT(1) * 1000000.
      DT2U = DT(2) * 1000000.
      DT3U = DT(3) * 1000000.
      DT4U = DT(4) * 1000000.
C  CONVERT XYZ COORDINATES TO MILLIMETERS TO PRINT TO SCREEN
      X1MM = X1*1000.
      X2MM = X2*1000.
      X3MM = X3*1000.
      X4MM = X4*1000.
      Y1MM = Y1*1000.
      Y2MM = Y2*1000.
      Y3MM = Y3*1000.
      Y4MM = Y4*1000.
      Z1MM = Z1*1000.
      Z2MM = Z2*1000.
      Z3MM = Z3*1000.
      Z4MM = Z4*1000.


      WRITE(*,93)DT1U,DT2U,DT3U,DT4U
93    FORMAT(/,5X,'THE DIFFERENCE IN TOA FOR THE PLANARITY CHECK'
     1            ' PINS IS',
     2  //,15X,'PIN T-1B: ',F6.1,' MICRO-SECONDS',
     3   /,15X,'PIN T-2:  ',F6.1,' MICRO-SECONDS',
     4   /,15X,'PIN T-3B: ',F6.1,' MICRO-SECONDS',
     5   /,15X,'PIN T-4:  ',F6.1,' MICRO-SECONDS')

      WRITE(*,95)X1MM,Y1MM,Z1MM,X2MM,Y2MM,Z2MM,X3MM,Y3MM,Z3MM,
     1            X4MM,Y4MM,Z4MM,VELAVG,TOLPMMM
95    FORMAT(//,5X,'THE XYZ COORDINATES OF THE IMPACT PLATE ARE:',
     1  //,21X,'X',10X,'Y',8X,'Z',
     2   /,5X,'PIN T-1B:   ',F8.3,3X,F8.3,1X,F8.3,'   MILLIMETERS',
     3   /,5X,'PIN T-2:    ',F8.3,3X,F8.3,1X,F8.3,'   MILLIMETERS',
     4   /,5X,'PIN T-3B:   ',F8.3,3X,F8.3,1X,F8.3,'   MILLIMETERS',
     5   /,5X,'PIN T-4:    ',F8.3,3X,F8.3,1X,F8.3,'   MILLIMETERS',
     6  //,5X,'THE Z COORDINATES OF THE IMPACT PLATE ARE BASED ON',
     7   /,5X,'THE AVERAGE VELOCITY ',F6.2,' M/SEC',
```

```
   8 //,5X,'THE TOLERANCE ON PLACEMENT OF THE TOA PINS IS',
   9  /,5X,'PLUS OR MINUS ',F5.3,' MILLIMETERS')

     WRITE(*,80)
     READ(*,*)

C  PERFORM CALCS TO DETERMINE MAX ANGLE OF ROTATION OF IMPACT PLATE
C  ALSO DETERMINE TOLERANCE ON ANGLE OF ROTATION

      IF (TOAMIN.EQ.TOA(1)) THEN
        R2=SQRT(X2*X2 + Y2*Y2)
        THETA2=ATAN(Z2/R2)
        R3=SQRT(X3*X3 + Y3*Y3)
        THETA3=ATAN(Z3/R3)
        R4=SQRT(X4*X4 + Y4*Y4)
        THETA4=ATAN(Z4/R4)
        THETAMAX=AMAX1(THETA2,THETA3,THETA4)
        IF(THETAMAX.EQ.THETA2) THEN
          THETATOL=ATAN(TOL/R2)
        ELSE IF (THETAMAX.EQ.THETA3) THEN
          THETATOL=ATAN(TOL/R3)
        ELSE
          THETATOL=ATAN(TOL/R4)
        ENDIF
      ELSE IF (TOAMIN.EQ.TOA(2)) THEN
        R1=SQRT(X1*X1 + Y1*Y1)
        THETA1=ATAN(Z1/R1)
        R3=SQRT(X3*X3 + Y3*Y3)
        THETA3=ATAN(Z3/R3)
        R4=SQRT(X4*X4 + Y4*Y4)
        THETA4=ATAN(Z4/R4)
        THETAMAX=AMAX1(THETA1,THETA3,THETA4)
        IF(THETAMAX.EQ.THETA1) THEN
          THETATOL=ATAN(TOL/R1)
        ELSE IF (THETAMAX.EQ.THETA3) THEN
          THETATOL=ATAN(TOL/R3)
        ELSE
          THETATOL=ATAN(TOL/R4)
        ENDIF
      ELSE IF (TOAMIN.EQ.TOA(3)) THEN
        R1=SQRT(X1*X1 + Y1*Y1)
        THETA1=ATAN(Z1/R1)
        R2=SQRT(X2*X2 + Y2*Y2)
        THETA2=ATAN(Z2/R2)
        R4=SQRT(X4*X4 + Y4*Y4)
        THETA4=ATAN(Z4/R4)
        THETAMAX=AMAX1(THETA1,THETA2,THETA4)
        IF(THETAMAX.EQ.THETA1) THEN
          THETATOL=ATAN(TOL/R1)
        ELSE IF (THETAMAX.EQ.THETA2) THEN
          THETATOL=ATAN(TOL/R2)
        ELSE
```

E-9

```
            THETATOL=ATAN(TOL/R4)
          END IF
        ELSE
          R1=SQRT(X1*X1 + Y1*Y1)
          THETA1=ATAN(Z1/R1)
          R2=SQRT(X2*X2 + Y2*Y2)
          THETA2=ATAN(Z2/R2)
          R3=SQRT(X3*X3 + Y3*Y3)
          THETA3=ATAN(Z3/R3)
          THETAMAX=AMAX1(THETA1,THETA2,THETA3)
          IF(THETAMAX.EQ.THETA1) THEN
             THETATOL=ATAN(TOL/R1)
          ELSE IF (THETAMAX.EQ.THETA2) THEN
             THETATOL=ATAN(TOL/R2)
          ELSE
             THETATOL=ATAN(TOL/R3)
          ENDIF
        ENDIF

        IF(THETAMAX.EQ.THETA1) THEN
           PINMAX='T-1B'
        ELSE IF (THETAMAX.EQ.THETA2) THEN
           PINMAX='T-2'
        ELSE IF (THETAMAX.EQ.THETA3) THEN
           PINMAX='T-3P'
        ELSE
           PINMAX='T-4'
        ENDIF

C   CHANGE THETAMAX AND THETATOL FROM RADIANS TO DEGREES
        THETAMAX = THETAMAX*1000.
        THETATOL = THETATOL*1000.

        WRITE(*,98)THETAMAX,THETATOL,PINMIN,PINMAX
98      FORMAT(/,2X,'THE MAX ANGLE OF ROTATION OF THE IMPACT PLATE IS: ',
     1          F6.3,' MILLIRADIANS',
     2          /,2X,'THE TOLERANCE ON THIS ANGLE OF ROTATION IS PLUS',
     3          ' OR MINUS: ',F6.3,' MILLIRADIANS',
     4          /,2X,'THIS ANGLE OCCURS BETWEEN PINS ',A4,' AND ',A4)

        WRITE(*,80)
        READ(*,*)

C   PERFORM CALCS TO DETERMINE CONSISTENCY OF TOA MEASUREMENTS.
C   THE Z COORDINATES ARE CALCULATED BY ASSUMING A PROJECTILE VELOCITY
C   EQUAL TO VELAVG.  THE THREE BASE POINTS ARE ASSUMED TO BE CORRECT.
C   THE TOLERANCE IS CONSIDERED ONLY FOR THE POINT BEING CHECKED.  THIS
C   TOLERANCE IS NOT THE ABSOLUTE TOLERANCE (TOL) BUT ONE-HALF THE
C   ABSOLUTE, IE, THE PLUS OR MINUS TOLERANCE (TOLPM).

C   CHECK PIN 1 BY USING EQN OF PLANE THRU PINS 2, 3, & 4
```

```fortran
        COEFF1 = (Y2-Y4)*(Z3-Z4) - (Y3-Y4)*(Z2-Z4)
        COEFF2 = (X2-X4)*(Z3-Z4) - (X3-X4)*(Z2-Z4)
        COEFF3 = (X2-X4)*(Y3-Y4) - (X3-X4)*(Y2-Y4)
        CONST = -(X4*COEFF1) + (Y4*COEFF2) - (Z4*COEFF3)
        Z1C = ((Y1*COEFF2) - (X1*COEFF1) - CONST)/COEFF3
        Z1CMM = Z1C * 1000.

        WRITE(*,100)COEFF1,COEFF2,COEFF3,CONST
100     FORMAT(//,18X,'**** CHECK LOCATION OF TOA PIN T-1B ****',
     1   //,5X,'THE EQUATION OF THE PLANE THROUGH TOA PINS 2, 3,',
     2   ' & 4 IS:',
     3   //,10X,E11.5,' X + ',E11.5,' Y + ',E11.5,' Z + ',E11.5,' = 0')

        Z1MIN = AMIN1(Z1,Z1C)

        IF(Z1MIN.EQ.Z1) THEN
C  CALCULATED VALUE OF Z1 IS GREATER THAN THE EXPERIMENTAL VALUE OF Z1
          ZDIF1MIN = ((Z1C/(Z1+TOLPM)) - 1.) * 100.
          IF(ZDIF1MIN.LE.0.) THEN
            WRITE(*,102)Z1CMM,TOLPMMM,Z1MM
102         FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-1B: ',F6.3,
     1                   ' MILLIMETERS',
     2           /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                   ' MILLIMETERS',
     4           /,5X,'OF THE EXPERIMENTAL VALUE:        ',F6.3,
     5                   ' MILLIMETERS')
          ELSE
            ZDIF1MAX = ABS((Z1C/(Z1-TOLPM)) - 1.) * 100.
            WRITE(*,104)Z1CMM,TOLPMMM,Z1MM,ZDIF1MIN,ZDIF1MAX
104         FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-1B:     ',F6.3,
     1                   ' MILLIMETERS',
     2           /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                   ' MILLIMETERS',
     4           /,5X,'OF THE EXPERIMENTAL VALUE:            ',F6.3,
     5                   ' MILLIMETERS',
     6   //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
     7    /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
     8    /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
     9   //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
     1    /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
     2    /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')
          ENDIF

C  CALCULATED VALUE OF Z1 IS LESS THAN THE EXPERIMENTAL VALUE OF Z1
C    THE CALCULATED VALUE OF Z1 IS GREATER THAN ZERO

        ELSE IF (Z1C.GT.0) THEN
          ZDIF1MIN=(((Z1-TOLPM)/Z1C) - 1.) * 100.
          IF(ZDIF1MIN.LE.0) THEN
            WRITE(*,106)Z1CMM,TOLPMMM,Z1MM
106         FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-1B: ',F6.3,
     1                   ' MILLIMETERS',
```

```fortran
2              /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
3                     ' MILLIMETERS',
4              /,5X,'OF THE EXPERIMENTAL VALUE:          ',F6.3,
5                     ' MILLIMETERS')
         ELSE
         ZDIF1MAX=(((Z1+TOLPM)/Z1C) - 1.) * 100.
         WRITE(*,108)Z1CMM,TOLPMMM,Z1MM,ZDIF1MIN,ZDIF1MAX
108      FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-1B:    ',F6.3,
1                     ' MILLIMETERS',
2              /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
3                     ' MILLIMETERS',
4              /,5X,'OF THE EXPERIMENTAL VALUE:          ',F6.3,
5                     ' MILLIMETERS',
6       //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
7        /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
8        /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
9       //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
1        /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
2        /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')
      ENDIF


      ELSE IF((Z1C-(Z1-TOLPM)).GT.0)THEN
         WRITE(*,200)Z1CMM,TOLPMMM,Z1MM
200      FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-1B: ',F6.3,
1                     ' MILLIMETERS',
2              /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
3                     ' MILLIMETERS',
4              /,5X,'OF THE EXPERIMENTAL VALUE:          ',F6.3,
5                     ' MILLIMETERS')


         ELSE IF(ABS(Z1C).LE.ABS(Z1-TOLPM))THEN
         ZDIF1MIN =ABS(1 - ((Z1-TOLPM)/Z1C)) * 100
         ZDIF1MAX =ABS(1 - ((Z1+TOLPM)/Z1C)) * 100
         WRITE(*,204)Z1CMM,TOLPMMM,Z1MM,ZDIF1MIN,ZDIF1MAX
           ELSE
         ZDIF1MIN =ABS((Z1C/(Z1-TOLPM)) - 1) * 100

         IF(ABS(Z1C).LE.ABS(Z1+TOLPM))THEN
         ZDIF1MAX =ABS(1 - ((Z1+TOLPM)/Z1C)) * 100
         ELSE
         ZDIF1MAX =ABS((Z1C/(Z1+TOLPM)) - 1) * 100
         ENDIF


         WRITE(*,204)Z1CMM,TOLPMMM,Z1MM,ZDIF1MIN,ZDIF1MAX
204      FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-1B:    ',F6.3,
1                     ' MILLIMETERS',
2              /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
3                     ' MILLIMETERS',
4              /,5X,'OF THE EXPERIMENTAL VALUE:          ',F6.3,
5                     ' MILLIMETERS',
6       //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
```

```
      7    /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
      8    /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
      9   //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
      1    /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
      2    /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')


        ENDIF

      WRITE(*,80)
      READ(*,*)

C  CHECK PIN 2 BY USING EQN OF PLANE THRU PINS 1, 3, & 4

      COEFF1 = (Y4-Y1)*(Z3-Z1) - (Y3-Y1)*(Z4-Z1)
      COEFF2 = (X4-X1)*(Z3-Z1) - (X3-X1)*(Z4-Z1)
      COEFF3 = (X4-X1)*(Y3-Y1) - (X3-X1)*(Y4-Y1)
      CONST = -(X1*COEFF1) + (Y1*COEFF2) - (Z1*COEFF3)
      Z2C = ((Y2*COEFF2) - (X2*COEFF1) - CONST)/COEFF3
      Z2CMM = Z2C * 1000.

      WRITE(*,110)COEFF1,COEFF2,COEFF3,CONST
110   FORMAT(//,18X,'**** CHECK LOCATION OF TOA PIN T-2 ****',
      1 //,5X,'THE EQUATION OF THE PLANE THROUGH TOA PINS 1, 3,',
      2 ' & 4 IS:',
      3 //,10X,E11.5,' X + ',E11.5,' Y + ',E11.5,' Z + ',E11.5,' = 0')

      Z2MIN = AMIN1(Z2,Z2C)

      IF(Z2MIN.EQ.Z2) THEN
C  CALCULATED VALUE OF Z2 IS GREATER THAN THE EXPERIMENTAL VALUE OF Z2
        ZDIF2MIN = ((Z2C/(Z2+TOLPM)) - 1.) * 100.
        IF(ZDIF2MIN.LE.0.) THEN
          WRITE(*,112)Z2CMM,TOLPMMM,Z2MM
112       FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-2: ',F6.3,
      1                 ' MILLIMETERS',
      2             /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
      3                 ' MILLIMETERS',
      4             /,5X,'OF THE EXPERIMENTAL VALUE:          ',F6.3,
      5                 ' MILLIMETERS')
        ELSE
          ZDIF2MAX = ABS((Z2C/(Z2-TOLPM)) - 1.) * 100.
          WRITE(*,114)Z2CMM,TOLPMMM,Z2MM,ZDIF2MIN,ZDIF2MAX
114       FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-2:      ',F6.3,
      1                 ' MILLIMETERS',
      2             /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
      3                 ' MILLIMETERS',
      4             /,5X,'OF THE EXPERIMENTAL VALUE:            ',F6.3,
      5                 ' MILLIMETERS',
      6   //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
      7    /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
      8    /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
```

```
      9     //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
      1      /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
      2      /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')
            ENDIF

C   CALCULATED VALUE OF Z2 IS LESS THAN THE EXPERIMENTAL VALUE OF Z2

          ELSE IF (Z2C.GT.0) THEN
              ZDIF2MIN=(((Z2-TOLPM)/Z2C) - 1.) * 100.
          IF(ZDIF2MIN.LE.0) THEN
              WRITE(*,210)Z2CMM,TOLPMMM,Z2MM
210           FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-1B: ',F6.3,
      1                   ' MILLIMETERS',
      2            /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
      3                   ' MILLIMETERS',
      4            /,5X,'OF THE EXPERIMENTAL VALUE:        ',F6.3,
      5                   ' MILLIMETERS')
          ELSE
          ZDIF2MAX=(((Z2+TOLPM)/Z2C) - 1.) * 100.
          WRITE(*,212)Z2CMM,TOLPMMM,Z2MM,ZDIF2MIN,ZDIF2MAX
212           FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-2:     ',F6.3,
      1                   ' MILLIMETERS',
      2            /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
      3                   ' MILLIMETERS',
      4            /,5X,'OF THE EXPERIMENTAL VALUE:           ',F6.3,
      5                   ' MILLIMETERS',
      6     //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
      7      /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
      8      /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
      9     //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
      1      /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
      2      /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')
            ENDIF

          ELSE IF((Z2C-(Z2-TOLPM)).GT.0)THEN
              WRITE(*,214)Z2CMM,TOLPMMM,Z2MM
214           FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-2: ',F6.3,
      1                   ' MILLIMETERS',
      2            /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
      3                   ' MILLIMETERS',
      4            /,5X,'OF THE EXPERIMENTAL VALUE:         ',F6.3,
      5                   ' MILLIMETERS')

              ELSEIF(ABS(Z2C).LE.ABS(Z2-TOLPM))THEN
          ZDIF2MIN =ABS(1 - ((Z2-TOLPM)/Z2C)) * 100
          ZDIF2MAX =ABS(1 - ((Z2+TOLPM)/Z2C)) * 100
          WRITE(*,216)Z2CMM,TOLPMMM,Z2MM,ZDIF2MIN,ZDIF2MAX
              ELSE
          ZDIF2MIN =ABS((Z2C/(Z2-TOLPM)) - 1) * 100

          IF(ABS(Z2C).LE.ABS(Z2+TOLPM))THEN
          ZDIF2MAX =ABS(1 - ((Z2+TOLPM)/Z2C)) * 100
```

```
          ELSE
          ZDIF2MAX =ABS((Z2C/(Z2+TOLPM)) - 1) * 100
          ENDIF


             WRITE(*,216)Z2CMM,TOLPMMM,Z2MM,ZDIF2MIN,ZDIF2MAX
  216        FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-2:      ',F6.3,
     1                   ' MILLIMETERS',
     2            /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                   ' MILLIMETERS',
     4            /,5X,'OF THE EXPERIMENTAL VALUE:             ',F6.3,
     5                   ' MILLIMETERS',
     6    //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
     7     /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
     8     /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
     9    //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
     1     /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
     2     /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')


          ENDIF

       WRITE(*,80)
       READ(*,*)


C  CHECK PIN 3 BY USING EQN OF PLANE THRU PINS 1, 2, & 4

       COEFF1 = (Y2-Y1)*(Z4-Z1) - (Y4-Y1)*(Z2-Z1)
       COEFF2 = (X2-X1)*(Z4-Z1) - (X4-X1)*(Z2-Z1)
       COEFF3 = (X2-X1)*(Y4-Y1) - (X4-X1)*(Y2-Y1)
       CONST = -(X1*COEFF1) + (Y1*COEFF2) - (Z1*COEFF3)
       Z3C = ((Y3*COEFF2) - (X3*COEFF1) - CONST)/COEFF3
       Z3CMM = Z3C * 1000.

       WRITE(*,120)COEFF1,COEFF2,COEFF3,CONST
  120  FORMAT(//,18X,'**** CHECK LOCATION OF TOA PIN T-3B ****',
     1   //,5X,'THE EQUATION OF THE PLANE THROUGH TOA PINS 1, 2,',
     2   ' & 4 IS:',
     3   //,10X,E11.5,' X + ',E11.5,' Y + ',E11.5,' Z + ',E11.5,' = 0')

       Z3MIN = AMIN1(Z3,Z3C)


       IF(Z3MIN.EQ.Z3) THEN
C  CALCULATED VALUE OF Z3 IS GREATER THAN THE EXPERIMENTAL VALUE OF Z3
          ZDIF3MIN = ((Z3C/(Z3+TOLPM)) - 1.) * 100.
          IF(ZDIF3MIN.LE.0.) THEN
             WRITE(*,122)Z3CMM,TOLPMMM,Z3MM
  122        FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-3B: ',F6.3,
     1                   ' MILLIMETERS',
     2            /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                   ' MILLIMETERS',
     4            /,5X,'OF THE EXPERIMENTAL VALUE:          ',F6.3,
```

```
      5                        ' MILLIMETERS')
            ELSE
              ZDIF3MAX = ABS((Z3C/(Z3-TOLPM)) - 1.) * 100.
              WRITE(*,124)Z3CMM,TOLPMMM,Z3MM,ZDIF3MIN,ZDIF3MAX
124           FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-3B:      ',F6.3,
     1                     ' MILLIMETERS',
     2                /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                     ' MILLIMETERS',
     4                /,5X,'OF THE EXPERIMENTAL VALUE:              ',F6.3,
     5                     ' MILLIMETERS',
     6      //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
     7       /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
     8       /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
     9      //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
     1       /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
     2       /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')
            ENDIF


C   CALCULATED VALUE OF Z3 IS LESS THAN THE EXPERIMENTAL VALUE OF Z3

          ELSE IF (Z3C.GT.0) THEN
            ZDIF3MIN=(((Z3-TOLPM)/Z3C) - 1.) * 100.
            IF(ZDIF3MIN.LE.0) THEN
              WRITE(*,220)Z3CMM,TOLPMMM,Z3MM
220           FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-3B: ',F6.3,
     1                     ' MILLIMETERS',
     2                /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                     ' MILLIMETERS',
     4                /,5X,'OF THE EXPERIMENTAL VALUE:         ',F6.3,
     5                     ' MILLIMETERS')
            ELSE
              ZDIF3MAX=(((Z3+TOLPM)/Z3C) - 1.) * 100.
              WRITE(*,222)Z3CMM,TOLPMMM,Z3MM,ZDIF3MIN,ZDIF3MAX
222           FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-3B:      ',F6.3,
     1                     ' MILLIMETERS',
     2                /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                     ' MILLIMETERS',
     4                /,5X,'OF THE EXPERIMENTAL VALUE:              ',F6.3,
     5                     ' MILLIMETERS',
     6      //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
     7       /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
     8       /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
     9      //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
     1       /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
     2       /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')
            ENDIF

          ELSE IF((Z3C-(Z3-TOLPM)).GT.0)THEN
            WRITE(*,224)Z3CMM,TOLPMMM,Z3MM
224           FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-3B: ',F6.3,
     1                     ' MILLIMETERS',
     2                /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
```

```
      3                ' MILLIMETERS',
      4             /,5X,'OF THE EXPERIMENTAL VALUE:        ',F6.3,
      5                ' MILLIMETERS')

             ELSE IF(ABS(Z3C).LE.ABS(Z3-TOLPM))THEN
        ZDIF3MIN =ABS(1 - ((Z3-TOLPM)/Z3C)) * 100
        ZDIF3MAX =ABS(1 - ((Z3+TOLPM)/Z3C)) * 100
            WRITE(*,226)Z3CMM,TOLPMMM,Z3MM,ZDIF3MIN,ZDIF3MAX
         ELSE
        ZDIF3MIN =ABS((Z3C/(Z3-TOLPM)) - 1) * 100

        IF(ABS(Z3C).LE.ABS(Z3+TOLPM))THEN
        ZDIF3MAX =ABS(1 - ((Z3+TOLPM)/Z3C)) * 100
        ELSE
        ZDIF3MAX =ABS((Z3C/(Z3+TOLPM)) - 1) * 100
        ENDIF


             WRITE(*,226)Z3CMM,TOLPMMM,Z3MM,ZDIF3MIN,ZDIF3MAX
226          FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-3B:     ',F6.3,
      1                ' MILLIMETERS',
      2             /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
      3                ' MILLIMETERS',
      4             /,5X,'OF THE EXPERIMENTAL VALUE:        ',F6.3,
      5                ' MILLIMETERS',
      6 //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
      7  /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
      8  /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
      9 //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
      1  /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
      2  /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')


         ENDIF

      WRITE(*,80)
      READ(*,*)

C  CHECK LOCATION OF PIN 4 BY USING EQN OF PLANE THRU PINS 1, 2, & 3

      COEFF1 = (Y2-Y1)*(Z3-Z1) - (Y3-Y1)*(Z2-Z1)
      COEFF2 = (X2-X1)*(Z3-Z1) - (X3-X1)*(Z2-Z1)
      COEFF3 = (X2-X1)*(Y3-Y1) - (X3-X1)*(Y2-Y1)
      CONST = -(X1*COEFF1) + (Y1*COEFF2) - (Z1*COEFF3)
      Z4C = ((Y4*COEFF2) - (X4*COEFF1) - CONST)/COEFF3
      Z4CMM = Z4C * 1000.

      WRITE(*,130)COEFF1,COEFF2,COEFF3,CONST
130   FORMAT(//,18X,'**** CHECK LOCATION OF TOA PIN T-4 ****',
      1 //,5X,'THE EQUATION OF THE PLANE THROUGH TOA PINS 1, 2,',
      2 ' & 3 IS:',
      3 //,10X,E11.5,' X + ',E11.5,' Y + ',E11.5,' Z + ',E11.5,' = 0')
```

```fortran
        Z4MIN - AMIN1(Z4,Z4C)

        IF(Z4MIN.EQ.Z4) THEN
C  CALCULATED VALUE OF Z4 IS GREATER THAN THE EXPERIMENTAL VALUE OF Z4
          ZDIF4MIN - ((Z4C/(Z4+TOLPM)) - 1.) * 100.
          IF(ZDIF4MIN.LE.0.) THEN
            WRITE(*,132)Z4CMM,TOLPMMM,Z4MM
132         FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-4: ',F6.3,
     1                   ' MILLIMETERS',
     2              /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                   ' MILLIMETERS',
     4              /,5X,'OF THE EXPERIMENTAL VALUE:          ',F6.3,
     5                   ' MILLIMETERS')
          ELSE
            ZDIF4MAX - ((Z4C/(Z4-TOLPM)) - 1.) * 100.
            WRITE(*,134)Z4CMM,TOLPMMM,Z4MM,ZDIF4MIN,ZDIF4MAX
134         FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-4:     ',F6.3,
     1                   ' MILLIMETERS',
     2              /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                   ' MILLIMETERS',
     4              /,5X,'OF THE EXPERIMENTAL VALUE:             ',F6.3,
     5                   ' MILLIMETERS',
     6         //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
     7          /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT'
     8          /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
     9         //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED'
     1          /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
     2          /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')
          ENDIF

C  CALCULATED VALUE OF Z4 IS LESS THAN THE EXPERIMENTAL VALUE OF Z4

        ELSE IF (Z4C.GT.0) THEN
          ZDIF4MIN=(((Z4-TOLPM)/Z4C) - 1.) * 100.
          IF(ZDIF4MIN.LE.0) THEN
            WRITE(*,230)Z4CMM,TOLPMMM,Z4MM
230         FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-4: ',F6.3,
     1                   ' MILLIMETERS',
     2              /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                   ' MILLIMETERS',
     4              /,5X,'OF THE EXPERIMENTAL VALUE:          ',F6.3,
     5                   ' MILLIMETERS')
          ELSE
            ZDIF4MAX - ABS(((Z4+TOLPM)/Z4C) - 1.) * 100.
            WRITE(*,232)Z4CMM,TOLPMMM,Z4MM,ZDIF4MIN,ZDIF4MAX
232         FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-1B:      ',F6.3,
     1                   ' MILLIMETERS',
     2              /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
     3                   ' MILLIMETERS',
     4              /,5X,'OF THE EXPERIMENTAL VALUE:             ',F6.3,
     5                   ' MILLIMETERS',
     6         //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
```

```
       7      /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
       8      /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
       9      //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
       1      /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
       2      /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')
              ENDIF

            ELSE IF((Z4C-(Z4-TOLPM)).GT.0)THEN
              WRITE(*,234)Z4CMM,TOLPMMM,Z4MM
234           FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-4: ',F6.3,
       1                    ' MILLIMETERS',
       2               /,5X,'IS WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
       3                    ' MILLIMETERS',
       4               /,5X,'OF THE EXPERIMENTAL VALUE:         ',F6.3,
       5                    ' MILLIMETERS')

              ELSE IF(ABS(Z4C).LE.ABS(Z4-TOLPM))THEN
              ZDIF4MIN =ABS(1 - ((Z4-TOLPM)/Z4C)) * 100
              ZDIF4MAX =ABS(1 - ((Z4+TOLPM)/Z4C)) * 100
                 WRITE(*,236)Z4CMM,TOLPMMM,Z4MM,ZDIF4MIN,ZDIF4MAX
              ELSE
              ZDIF4MIN =ABS((Z4C/(Z4-TOLPM)) - 1) * 100

              IF(ABS(Z4C).LE.ABS(Z4+TOLPM))THEN
              ZDIF4MAX =ABS(1 - ((Z4+TOLPM)/Z4C)) * 100
              ELSE
              ZDIF4MAX =ABS((Z4C/(Z4+TOLPM)) - 1) * 100
              ENDIF


              WRITE(*,236)Z4CMM,TOLPMMM,Z4MM,ZDIF4MIN,ZDIF4MAX
236           FORMAT(//,5X,'THE CALCULATED VALUE OF PIN T-4:    ',F6.3,
       1                    ' MILLIMETERS',
       2               /,5X,'IS NOT WITHIN THE PLACEMENT TOLERANCE: ',F5.3,
       3                    ' MILLIMETERS',
       4               /,5X,'OF THE EXPERIMENTAL VALUE:            ',F6.3,
       5                    ' MILLIMETERS',
       6      //,5X,'THE MINIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
       7      /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
       8      /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT',
       9      //,5X,'THE MAXIMUM PERCENT DIFFERENCE BETWEEN THE CALCULATED',
       1      /,5X,'AND EXPERIMENTAL VALUES (CONSIDERING THE PLACEMENT',
       2      /,5X,'TOLERANCE) IS: ',F7.2,' PERCENT')


              ENDIF

          WRITE(*,80)
          READ(*,*)

1000  END
```

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 1993	3. REPORT TYPE AND DATES COVERED Technical - 24 Jan 90 - 31 Dec 92

4. TITLE AND SUBTITLE Performance Tests with the WES 4-ft-Diameter Vertical Gas Gun	5. FUNDING NUMBERS MIPR 90-594 MIPR 91-571 MIPR 92-573
6. AUTHOR(S) Howard G. White	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) USAE Waterways Experiment Station Structures Laboratory 3909 Halls Ferry Road Vicksburg, MS 39180-6199	8. PERFORMING ORGANIZATION REPORT NUMBER Technical Report SL-93-11

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Nuclear Agency, 6801 Telegraph Road Alexandria, VA 22310-3398	10. SPONSORING/MONITORING AGENCY REPORT NUMBER DNA-TR-93-16

11. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Twenty-two tests have been conducted with the WES 4-ft-Diameter Vertical Gas Gun. These tests were conducted over the entire operating range of the gun (0 to 2,070 kPa). The projectile velocity on these tests varied from 5.4 to 71 m/sec. The measured velocities were on average, about 90 percent of the values predicted by the mathematical model of the gun's performance. The accuracy of the velocity measurement is ±4.6 percent.

Safety issues associated with the initial testing and routine operation of the gas gun are discussed. Predictive techniques for far-field ground motion and airblast are presented, along with measured data. A mathematical model for predicting the projectile velocity as a function of gas gun's reservoir pressure is presented and compared with test data.

"Nuisance" data collected on these tests indicates there is no potential for ground shock or airblast damage to buildings in the local area from the operation of the gas gun. The noise generated from firing the gun, is within allowable levels and caused little disturbance in surrounding areas.

14. SUBJECT TERMS Gas gun Instrumentation calibration Ground motion Projectile impact Ground shock	15. NUMBER OF PAGES 98
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR